Inlet Closure and Morphological Behavior in a Northern California Estuary: The Case of the Russian River

By

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conducted and provided in this text does some justice to the outstanding work that she has done.

Abstract

The Russian River Estuary forms the terminus of the 3847 km^2 Russian River watershed in northern California. The inlet that provides communication between the ocean and the estuary closes each year, causing ponding of the estuary, allowing stratification to occur, and in some cases, leading to the flooding of local property. Closure has occurred at this site at least since the first written accounts by Russian settlers described the area in the early nineteenth century, and it is reasonable to assume that this behavior is natural and that the local ecology has adapted to it. These closures are the result of wave-induced sediment transport, either in the form of shore-parallel (longshore) currents which interact with tide- or river-induced inlet currents, or the onshore movement of discrete sandbars. This site provides an excellent opportunity to answer many questions regarding inlet morphology and closure. The first reason for this is that the frequency of closure events in this estuary set this apart from the more common seasonally closed or permanently open estuaries which exist throughout the world. The estuary closes between five and fifteen times each year, and thus provides many chances to study the possible relations between these events and the environmental conditions that influence them. Second, the Russian River varies in discharge throughout the year from less than 100 cubic feet per second (cfs) to more than 90,000 cfs. These river flows interact with the active wave climate and moderate tides that are characteristic of the northern California coastline. These three processes constantly interact, and both the cross-sectional and planform geometry of the inlet are in a nearly constant state of adjustment in response to the changes in these processes at the daily, seasonal, and annual timescales. Lastly, a resident

of Jenner, California, at the mouth of the river, has provided a unique and unprecedented dataset. This dataset includes daily photographs taken of the inlet from 1990 to 2006, and written observations of the condition of the inlet spanning over 30 years. Additionally, offshore wave measurements, both offshore and in-estuary tide measurements, and river discharge measurements are available at this site. In short, enough components are present in this case to study the relations between inlet morphology and environmental forcing over a period that includes a full range of hydrologic and climatic conditions.

This work includes two separate studies. The first study analyzes the effectiveness of a simple parametric model at predicting closure events. The second is a study of inlet morphology, shape, and migration that takes into account interactions between waves, river discharge, and tides at daily, seasonal, and annual timescales. Both studies required the quantification of the inlet characteristics which were visible in the provided photographic dataset. Estimates of inlet width, length, and position on the barrier beach were obtained by comparing the photographs of the inlet with satellite imagery available from GoogleEarth. This was possible because several landmarks on the barrier beach are visible in the provided photographic record of the inlet as well as in the satellite imagery. The exact distances between these landmarks were obtained from the satellite imagery, and the dimensions of the inlet were estimated by comparing the size of the inlet with these known distances. Additionally, the photographs of the inlet were used to classify the daily shape of the inlet from 1990 to 2006.

The study of inlet closure applied methods of closure prediction developed by O'Brien (1971) and Goodwin (1996), and introduced several other methods. The period lasting from 1999 to 2006 was used as a test period because this was the only period of time for which there were no significant gaps in any of the available datasets. Each tested method relied on a non-dimensional index to predict closure. This index varied by method, and generally consisted of a ratio of a term representing wave power to terms that represented either tide power, stream power, or both. The important assumption used in this study was that time periods consisting of relatively high wave influence or relatively little tide or river influence coincide with periods of high on-shore sediment transport and deposition in the inlet. Ultimately, one of the methods introduced in this study provided the best results. When compared to the closure record from 1999 to 2006, it reproduced over 80 percent of the closure events. A subsequent sensitivity analysis showed that near-shore wave height estimates and offshore tide measurements are important for accuracy, whereas parameters such as the bottom slope of the inlet channel, and the group velocity at the inlet are less important.

The study of inlet morphology, shape, and migration compared the effects of tides, river discharge, and waves at several time scales. A system was developed to classify the inlet into a set of shapes, and this was used associate specific inlet shapes with characteristic environmental forcings or risks of closure. Generally, the more curvilinear inlet configurations were found during lower discharges and higher inlet lengths, and inlets that were exceedingly curvilinear (or "meandering") had a significantly high risk of closing within two weeks. A comparison of the inlet width and length showed that both of these parameters are controlled by both tides and river discharge, but that the influence of these factors varied throughout the year. Specifically, high discharges or spring tide ranges produced smaller inlet lengths and large widths, whereas low discharges or neap tides resulted in greater inlet lengths and smaller widths. This study also showed that there is a strong relationship between river discharge and the width and length of the inlet during the wetter months of the year, while tides had a much stronger relationship with these parameters during the drier months. This suggests that a threshold, originally suggested by Komar (1996), may exist which indicates whether tides or river discharge control inlet morphology. To investigate this, the width of the inlet was modeled for the year 2003 by using a river discharge threshold to indicate when to estimate width based on tides or river flow. Estimates were made by fitting the width data to tide or discharge measurements, respectively, and producing relationships between inlet width and the tide range or river discharge. An analysis of inlet migration showed that a general yearly migration pattern exists, but that this pattern may have shifted after 1994. Finally, the study found that the phenomenon of inlet closure has different explanations that depend on the time scale of concern. At the time scale of days, closure is likely caused by the change in sediment transport that accompanies a sudden shift in the strength of the local waves, tides, or river flow. However, tides don't appear to have any effect on the seasonal closure patterns of the inlet. At the time scale of years, both tides and waves become relatively unimportant as only the river discharge appears to have any relation to the yearly inlet closure pattern.

Chapter 1. Introduction

1.1 Why are Inlets Important?

By the definition of Escoffier (1940), an inlet is a “short, narrow waterway that connects a bay, lagoon, or an estuary to a larger body of water, generally a sea.” Within this definition, there are many subsets, since tidal inlets form in virtually every region of the world. Tidal inlets represent a natural system of reversing currents due to tides, variable quantities of fresh-water flow contributed by land drainage, and different levels of wave activity acting along the ocean margin of the inlet (Komar, 1996). The exchange with the ocean makes these systems important because it allows them to facilitate unique ecological environments and safe harbors for man-made vessels.

Inlets are frequently used as entrances to harbors and are important to navigation (Escoffier 1940). The importance of New England tidal inlets as navigation ways to harbors is evidenced by the fact that over half of the moderate to larger tidal inlets (width > 100 m) are stabilized by jetties (FitzGerald et al., 2002). Inlets are modified in order to secure their location and stability, so they can serve as reliable pathways from the ocean to economically important harbors and embayments. The use of tidal inlets for navigational purposes calls for deep inlet channels that do not shift with time or require frequent dredging. The U.S. Army Corps of Engineers (COE) has driven a large amount of the research on tidal inlets. The Corps’ interest in this research stems from its responsibilities for navigation, beach erosion prevention and control, and flood control. Tasked with the creation and maintenance of navigable U.S. waterways, the Corps routinely dredges millions of cubic yards of material each year from tidal inlets that connect the ocean with bays, estuaries, and lagoons (Escoffier, 1940).

Many estuaries form the basis of highly valuable and often unique ecosystems. They provide nursery, resting, and feeding grounds for many species. (Hibma et al., 2004). Along the California coast, tidal inlets are the entry points of salmonids which migrate upstream to lay their eggs. These species require inlets to stay open for much of the year in order for populations to remain stable. From a water quality standpoint, a beneficial inlet configuration permits the efficient flushing of an embayment and maintains a suitable salinity regime for its fisheries resources (DiLorenzo, 1988). Restricted flushing during the months of inlet closure in natural systems can lead to degradation of water quality in the estuary/lagoon, which can have negative impacts not only for local ecology, but for people who use the estuary waters for irrigation and other purposes (Ranasinghe & Pattiaratchi, 2003).

Throughout this text, inlets will often be referred to as either “stable” or “unstable”. In accordance with the literature reviewed herein, the term “stable” is associated with inlets that remain open to the ocean, whereas the term “unstable” refers to inlets that fill with sediment and sometimes close, preventing communication between ocean and estuary waters.

1.2. The Russian River Estuary

The inlet of the Russian River Estuary is the site of the current study. The estuary is located roughly 60 miles north of San Francisco on California's Sonoma Coast (see Figure 1.1). The site is significant because of its use by several native fish species, and because of its history of seemingly sporadic closure. Closure of the river mouth has been an issue of concern both for agencies that have attempted to secure a permanently navigable entrance at the mouth and for the species within the estuary that are affected by changes in water quality associated with inlet closure.

Figure 1.1. Location of Russian River Estuary on California's Coastline. Photograph available from http//:visibleearth.nasa.gov

1.2.1. Hydrology

The Russian River watershed encompasses 3847 km^2 in Sonoma, Mendocino, and Lake counties. The 11 km long estuary extends from the mouth of the Russian River upstream to the community of Duncans Mills (Martini-Lamb, 2005). The stream flow of the river is highly variable. Since the construction of Coyote Valley Dam in 1958, the stream flow measured 11 miles upstream from the river mouth has fluctuated from a peak flood discharge of 93,000 cfs to a minimum of below 100 cfs (Goodwin and Cuffe, 1993). The size and seasonality of the river are likely to have been different before changes in land-use altered the flow conditions. Flows in the Russian River have been supplemented by diversions from the Eel River since 1929. The flows in the river are regulated partially by Coyote Dam in Mendocino County and Warm Springs Dam on Dry Creek, a major tributary of the Russian River in Sonoma County. These dams release minimum flows for fish during the dry summer months, which has reduced the variability of the flows during the summer. During winter flow conditions and significant storm events the flood peaks are reduced due to the operation of the reservoirs for flood control purposes (Goodwin and Cuffe, 1993). This regulation often leads to flow conditions that remain unchanged for weeks at a time, since the meteorological variability is curbed by upstream dam release management. It is unclear whether this current control of the river provides different inlet closure habits than those that would be found before the initial human contact in the region. Goodwin and Cuffe (1993) noted that the limited sources of data imply that the massive sedimentation observed in other California coastal lagoons has not occurred in the Russian River, although the limited historic data is not conclusive. A comparison of river cross-sections taken at the Highway One Bridge (River mile 2.1) and

Duncans Mills (River Mile 5.8) by the Sonoma County Water Agency shows that there have been no long-term change in the bathymetry between 1971 and 1992 at these structures.

The minimum discharge in the Russian River at Hacienda Bridge can differ depending on normal year, dry year or critical year flow requirements as established by the State Water Resource Control Board Decision 1610 (April 1986). During normal years, minimum flow requirement in the Russian River between Dry Creek and the river mouth are 125 cfs, while during dry and critical years the minimum flow requirements between Dry Creek and the mouth are 85 cfs and 35 cfs, respectively (Goodwin and Cuffe, 1993).

1.2.2. Tide Conditions

By the classification of Hayes (1980), the Sonoma coast is "mesotidal", with a maximum tide range of approximately 2.7 meters. Neap (low range) tides, are usually about 1 meter in range. The tidal regime is mixed, with each day containing two unequal peaks and troughs in ocean water elevation. These conditions are normal for the majority of the northern California coastline, and are generally too weak to maintain open tidal inlets, except in cases where tidal estuaries receive significant year-round river flows or when the topography allows large inter-tidal volumes of water to enter the estuary. Often, as with the Russian River Estuary, California inlet systems are associated with small tidal prisms. The tidal prism is known formally as the volume of water passing through the inlet over a complete floodtide or ebbtide (O'Brien, 1971). An approximate estimate of the maximum tidal prism in the Russian River Estuary was 1750 acre-feet, and 1300 acre-feet for the mean tidal prism in 1992 based on a study by Goodwin and Cuffe (1993). The authors of the study noted that historic records indicate that this tidal prism is approximately the same or less than conditions in 1876. Ultimately, the study concluded that a substantial increase in tidal prism would be required to maintain the estuary open to tidal circulation at all times. Maintaining a permanently open estuary would require repeated dredging operations, which could have large economic and environmental drawbacks.

1.2.3. Littoral Transport

Sediment transport in the immediate vicinity of the Russian River is thought to be low. Investigations regarding near-shore sediment transport by Johnson (1959), Cherry (1964), and Minard (1971) conclude that there is an extremely low intensity of sediment movement in the littoral zone near the rivermouth. This may be due to the fact that the barrier beach adjacent to the river is limited in length, and separated by large rock headlands at either end, possibly limiting longshore drift of sediments from outside littoral cells. According to Goodwin and Cuffe (1993) onshore movement of material discharged from the river occurs during summer months when long period waves transport the sediment landward, rebuilding the beach that winter waves and river outflows removed. This type of sediment movement, often referred to as "cross-shore transport" is observed in many studies and is often assumed to be the dominant cause of inlet closure (e.g. Ranasinghe and Pattiaratchi, 1998). Data obtained in the current study suggest that longshore transport may actually play a significant role, in addition to cross-shore transport, despite the aforementioned observations of low levels of transport at the mouth of the river. This will be discussed further in later sections. Surprisingly, sediment transport originating from the river itself has not caused any significant change in the size and shape of the estuary (Goodwin and Cuffe, 1993). This is uncommon for California estuaries, which generally suffer from ongoing or historical sedimentation as a result of land-use changes.

1.2.4. Climate

The general climate of the region is dominated by the westerly flow of marine air from the Pacific Ocean (Rice, 1974). A wet, winter season exists from October to May, and dry, summer months extend from June through September. The majority of the annual precipitation occurs between October and May, usually in a few events of relatively short duration. Wind speed and direction of wind observations collected at Point Reyes over a four-year period show that prevailing winds are from the northwest and west (Goodwin and Cuffe, 1993).

1.2.5. Wave Conditions

In general, the coastline of Sonoma County is an area of relatively high wave energy (de Graca, 1976; Johnson, 1959). Both locally generated (seas) and remotely generated (swell) waves are present at this coastline. According to Rice (1974), the predominant wave in the study area is from the northwest with an average period from 12 to 16 seconds. Significant wave heights for both sea and swell are highest during the winter months of November through January. During the summer months of June through August, locally generated waves (seas) have a relatively higher significant wave height, due to the local coastal winds generated during these months (Goodwin and Cuffe, 1993).

The local topography restricts the window for arriving waves. Headlands on either end of the beach extend far enough to block waves arriving from the direct north or south. Additionally, the retreat of the coastline due to long-term erosion has left behind several rock outcroppings within 500 m of the shoreline along the northernmost portion of the beach. It is likely that these outcroppings reduce the energy of incoming waves to some extent. Figure 1.2 gives an illustration of these outcroppings. As a result of these conditions, the river historically flows seaward at the north end of the barrier beach where wave power is the least (Rice, 1974). Figure 1.3 is an image of the river discharging at a point slightly south of the northern boundary of migration along the barrier beach.

Figure 1.2. Waves washing over the barrier beach of the Russian River Estuary. Offshore rocks visible in the background

Figure 1.3. Russian River inlet (facing west). Offshore rocks and northern headland visible in the background. Courtesy of Elinor Twohy

1.2.6. *History*

The earliest written reference to the Russian River appears in the Spanish land grant (the Bodega Grant) of July 19, 1843 which refers to “la boca del Rio Ruso” (Gudde, 1969). The Spanish claims were taken over by the U.S. in 1846 and development of the watershed began on a large scale. The most significant impacts on the watershed of the Russian River have been logging, agriculture, cattle and sheep ranching, the construction of dams and water diversions, and the extraction of gravel from the bed of the river (Goodwin and Cuffe, 1993). According to Rice (1974), since the first settlers came to the lower portions of the Russian River, interest has developed over methods of achieving a navigable waterway between the river and the sea. Several studies concerning the feasibility of keeping the inlet open permanently have been conducted, including those of Rice (1974), Johnson (1967), and the Sonoma Couty Planning Commision (1957).

Attempts at maintaining a navigable inlet began with the Jenner Jetty, which was completed in 1941. The purpose of the jetty was to allow gravel barges to sail to San Francisco Bay. Soon after completion, it was realized that the jetty had failed in its original purpose but did enhance fish migrations to and from the river. The only other active attempt at securing a navigable inlet was made in the mid 1960’s by a gravel mining interest using continuous dredging techniques. This operation “not only failed to keep the river mouth open but alarmed the public as to the possible adverse environmental ramifications” (Rice, 1974). More recently, studies have focused on exploring the effects of closure on the ecology of the estuary and on developing management plans to prevent prolonged closure and the associated flooding and property damage.

Historical accounts by local residents and records maintained by the County (Schrad, 1992) show that the estuary remains open during periods of low wave intensity and moderate to high freshwater inflows. According to Heckel (1994), the inlet closes most often in the spring, summer, and fall when river flows are relatively low and long period waves transport sand landward, rebuilding the beach that was removed by winter waves and river outflows. The closure of the estuary temporarily eliminates tidal exchange and creates ponding of the river, which results in a gradual increase of the water level in the estuary. This ponding can inundate building foundations, residential yards, and agricultural lands. Damages to property have been limited by artificial breaching of the barrier beach (see figure 1.4), a practice which has been undertaken by the Sonoma County Department of Roads "at least since living memory" according to Schrad (1992). Breaching is performed in accordance with the Russian River Estuary Management Plan outlined in the Russian River Estuary Study of 1992-1993 conducted by Goodwin and Cuffe (1993). The management plan calls for breaching of the sandbar when the estuary water surface level is between 1.4 and 2 meters as read at the Jenner gage (Martini-Lamb, 2005).

Figure 1.4. Artificial breaching of the Russian River Estuary. Courtesy of Elinor Twohy.

1.2.7. Environmental Concerns

Inlet closure in an estuarine environment gives rise to a number of environmental effects, not all of which are completely understood. Several recent studies have attempted to add to the understanding of the effects of inlet closure and breaching on the ecology of the Russian River Estuary (Goodwin and Cuffe, 1993; Martini-Lamb, 2005).

The effects of closure on estuarine water quality are probably the most well understood of the environmental issues studied in this region. The Russian River Estuary often experiences stratification after the inlet closes. An open inlet allows tidal fluctuations and river flow to flush water out of the estuary periodically. When the inlet closes, these tidal fluctuations become absent. This sudden lack of mixing processes leads to elevated water temperatures and anaerobic conditions at the estuary bed. Fish kills and a stressed ecosystem are associated with these conditions. If the inlet channel remains closed and the freshwater inflows are small compared with the seepage losses and evaporation, the estuary can become hypersaline, with observed salinities exceeding 80 ppt (Goodwin and

Cuffe, 1993). Although short-term anoxic events occur in the bottom of the estuary throughout much of the year, closures sometimes greatly increase the severity of these events (Martini-Lamb, 2005).

Artificial breaching may also affect the water quality in the estuary. For example, breaching the estuary at levels greater than 2.4m (8.0ft) floods the nearby Willow Creek marsh, which becomes anoxic during summer months due to low water inflow and high biochemical oxygen demand, and results in the subsequent draining of the poor quality water into the estuary (Sonoma County Water Agency and Merritt Smith Consulting, 2001). Since it is uncertain how long closure periods lasted before upstream water management changed the flow conditions into the estuary, the effects of artificially breaching the barrier beach on the local ecology is not completely clear. During the 1980's, concerns were raised regarding this issue. The Department of Planning, Sonoma County, and the California State Coastal Conservancy initiated a study to identify any adverse impacts associated with artificial breaching and to develop a management plan for the estuary (Goodwin and Cuffe, 1993).

Within all of these aforementioned studies, a large emphasis has been placed towards understanding how to conjunctively manage the estuary and allow local salmonid populations to thrive. In the Russian River alone, there are three federally listed salmonids found: central California coast steelhead (*Ohcorhynchus mykiss*), California coastal Chinook salmon (*O. tshawytscha*), and central California coast coho salmon (*O. kisutch*) (Martini-Lamb, 2005). This adds a level of difficulty to the management problem, because the state of the estuary can have multiple effects on these species. Since salmon live in both fluvial and marine environments during their lifetimes, an open inlet is necessary for them to be able to migrate between environments. Also, a closed estuary can extend the period of time that juvenile salmon are subjected to poor quality water and predation by pinnipeds (Martini-Lamb, 2005). Goodwin and Cuffe (1993) argue that the correlation between the timing of smolt releases at Warm Springs hatchery and artificial breaching during spring will prevent impoundment of out-migrating salmon.

1.3. Motivation

There are many reasons to study estuarine tidal inlet systems. One of the most prominent reasons is that there are many unanswered questions about channel stability and morphology, as well as questions about the roles of the many influencing factors such as tides, river processes, waves, localized turbulence, bottom friction, and littoral transport. Due to the complex interaction of these processes, inlets are believed by many researchers to be some of the most complex environments within the coastal zone (Komar, 1996).

Estuarine inlet systems also bridge a gap between coastal engineering and river mechanics. The field of coastal engineering has advanced extensively over the past 90 years, due in large part to the work of researchers such as Escoffier (1940), O'Brien (1931, 1971), Jarrett (1976), Bruun (1986), and many others, and has fallen largely under the management of successful U.S. Army Corps of Engineers (COE) research programs. River mechanics has been a well established field for over a century, and has built a considerable understanding of water movement and processes such as turbulence and sediment transport. Estuarine inlet systems do not fall exclusively into the category of either river mechanics or coastal engineering, because they are at any time governed both by fluvial and coastal processes. The degree to which these systems adhere to either coastal or riverine processes is not completely understood, and answers may yet be found that blend principles from both sides.

The Russian River Estuary is a good example of a system that is controlled by both river mechanics and coastal processes. This system experiences inlet closure and exhibits distinct daily, seasonal and annual patterns in morphological behavior. Furthermore, there are many stakeholders associated with the estuary, including parties concerned with the ecology and survival of salmonid species and local residents and farmers affected by flooding after inlet closure. A better understanding of the behavior of the estuary in response to natural (varying flow conditions, sporadic closure), and artificial (manual breaching of the inlet) processes will serve the needs of all of the stakeholders involved with the region.

1.4. Objectives

The purpose of this thesis is to provide insight into the complex interrelations between environmental forcings and morphology in an estuary where neither tides nor river flow can be neglected. To address this purpose, this paper has two key objectives. The first is to investigate the usefulness of a simple parametric model in modeling the closure events of the Russian River. The basis for this is to show whether a simple model is a sufficient alternative to a computationally expensive two- or three-dimensional numerical model. The second objective is to relate inlet morphology and closure to the environmental forcing of waves, tides, and river flow, using the available data. This objective includes the analysis of inlet migration, shape, closure, and physical dimensions at daily, seasonal, and annual timescales.

Chapter 2 provides a literature review that traces the development of inlet research to its current state. The writing in this chapter is purposefully broad, in order to address the number of related scientific fields that overlap with the study of inlets, and to account for the extensive set of studies that have influenced this thesis. Chapters 3 and 4 are presented as drafts of journal articles which address the objectives stated above. Chapter 3 addresses the phenomenon of inlet closure by presenting and comparing several parametric models. Chapter 4 relates many of the relevant environmental processes to various morphological aspects of the Russian River inlet. Finally, Chapter 5 presents a conclusion and summarizes the key findings of this study.

Chapter 2. Literature Review

2.1. Occurrence and behavior of unstable tidal inlets

Research has shown that seasonally open tidal inlets usually occur in micro- or meso-tidal wave-dominated coastal environments, which exhibit strong seasonal variations of streamflow and wave climate. They are generally small (10-500m in width, 10-1000m length, 1-3m depth) and they often close to the ocean seasonally due to the formation of a sand bar across the entrance (Ranasinghe and Pattiaratchi, 2003). A majority of seasonally open tidal inlets are located on sheltered embayed beaches. In many cases, these inlet close seasonally during summer when the streamflow is low and long-period swell waves dominate, or when longshore transport rates are high. Many seasonally closed tidal inlets are found on the southeastern and southwestern coasts of Australia, the southern coast of South Africa, the southeastern coast of Brazil, and the southwestern coasts of India and Sri Lanka. In South Africa alone, about 70% of estuaries are unstable and close, with most of them located on the eastern seaboard between the cities of East London and Durban (Stretch and Parkinson, 2006).

The conditions noted by Ranasinghe and Pattiaratchi (2003) are not general for all unstable inlets. Very small inlets in particular (10-100 m in width, 10-500m in length, 1-2 m in depth) sometimes exhibit characteristics that are vastly different than those of the more commonly studied larger inlets. For example, for the oceanic inlets plotted in the publication by Jarrett (1976), the average value for the ratio of inlet width to depth for inlets is 337 whereas the average value of the same ratio is 23 for smaller Chesapeake

Bay inlets. Additionally, within smaller tidal inlets characterized by large flow area variations with tidal stage, the maximum velocity is significantly lower than that observed in the larger inlets (0.35 m/s vs 1 m/s) (Byrne et al., 1980). Examination of the relationship between inlet width and depth suggests a departure between the oceanic inlets and the smaller natural and model inlets at throat area values between 100-500 m^2.

2.2. History and Progression of Inlet Studies

The origins of inlet research are rooted in practices meant for ensuring safe navigation into harbors and embayments. The earliest analysis of inlets concerned surveys of shifting and shallow channels to provide maps for mariners. Surveys have been made at frequent intervals at many inlets throughout the world; for some inlets, records go back more than a century (O'Brien, 1971). Data was initially taken in efforts to make sure that inlet bathymetry hadn't changed to a point that was dangerous for transportation, but there were aspects of the inlet analyses that were left out in the process. Deficiencies in the data regarding the dynamics of inlets are understandable because studies were made primarily for navigational purposes, and there was an inadequate theoretical basis for either planning field observations or the productive use of the data (O'Brien, 1971).

LeConte (1905) was among the first to actually study these systems from a strictly scientific point of view. His study investigated the relationship between the cross-sectional area of a tidal inlet and the amount of water that enters and leaves the estuary or lagoon in each tidal cycle. His work was greatly expanded upon by O'Brien (1931), who developed an empirical relation between the inlet cross-sectional geometry and this volume of water that passes through the inlet in each tidal cycle, based on data taken from many inlets. His work marked a huge advance in the field, and was the basis for much of the later research that provides us with our current understanding of inlet cross-sectional stability. However, this work didn't account explicitly for the reasons that such a relation could exist. Escoffier's (1940) analysis dealt with this issue by showing that inlets attain specific geometries based on the velocities of the inlet currents, which either allow or prevent sediment deposition. He noted that the velocities of these currents are functions of the quantity of water traversing the inlet in a given time period, which would explain why inlets with large tide ranges tended to have larger cross-sectional areas. An analysis necessary to calculate such velocities was introduced by Keulegan (1967), who developed his theory on inlet velocities by effectively reproducing inlet velocity patterns in three tidal inlets on the east coast of the United States. Despite these pioneering works, many questions still remained about inlet stability and morphology. The complexity of these systems made it difficult to understand the role of the many additional relevant processes.

To address this, the COE began an initiative known as the General Investigation of Tidal Inlets (GITI) in the 1950s. The Corps' interest in tidal inlet research stemmed from its responsibilities for navigation, beach erosion prevention control, and flood control (O'Brien, 1971). The GITI program was developed to provide quantitative data for use in design of inlets and inlet improvements. It was designed to meet the following objectives:

(1) To determine the effects of wave action, tidal flow, and related phenomena on inlet stability and on the hydraulic, geometric, and sedimentary characteristics of tidal inlets

(2) To develop the knowledge necessary to design effective navigation improvements, new inlets, and sand transfer systems at existing tidal inlets

(3) to evaluate the water transfer and flushing capability of tidal inlets

(4) to define the processes controlling inlet stability

This initiative led to an expanded effort to investigate many aspects of tidal inlet systems. O'Brien (1969) reproduced his relationship between inlet cross-sectional geometry and tidal volume (which he defined as "tidal prism"), using newly available data. His work was immediately continued by Nayak (1971), Johnson (1973), and Jarrett (1976). Jarrett's analysis is the most extensive and provides inlet area-tidal prism empirical relations for natural and jettied inlets based on data taken from the Pacific, Gulf, and East coasts of the United States. Many other researchers have continued to investigate this relation, and their work will be covered in the following sections. During this period, many other advances were made, and researchers such as Bruun and Gerritsen (1960), O'Brien (1971) and Bruun (1978) used newly available knowledge about sediment transport to explore the concept of inlet stability, which had only been studied by Escoffer (1940) up to that point. Many of the studies sparked by the GITI have become the basis for our current understanding of tidal inlet behavior, and the COE eventually produced an extensive guide for tidal inlets that includes the work of many of the major contributors in the field (see COE, 2002).

More recently, tidal inlet research has expanded to include environmental effects and studies of morphological change in large systems. For example, a variation of O'Brien's (1969) inlet area-tidal prism relation has been used to understand changes in the gaps between islands in the Dutch Wadden Sea as a result of large-scale human modification of the water body (Kragtwijk et al. 2004). Additionally, the relationship between inlet stability and various water quality changes in estuaries and lagoons has also gained much attention. It is presently unclear how estuarine and lagoonal environments respond to seasonal or infrequent closure of inlets (Martini-Lamb, 2005). Future research will likely address these areas by finding scaling relations for inlet analysis and by studying how varying stability behaviors of tidal inlets can affect the ecology of an adjacent tidal basin. Much work is also needed to explain the phenomena of inlet closure and breaching in systems with significant river inflows, which have received little attention to date.

2.3. Studies of the Cross-Sectional Stability of Tidal Inlets

Certainly the most extensively studied relation in tidal inlet research has been the relation between inlet cross-sectional area and tidal prism, sometimes known as the "O'Brien" or "Jarrett" relation. For the most part, it has been the focus of a large amount of attention because of its usefulness in design of inlet systems for commercial ports. However, it is also used as a predictor of inlet response to perturbations in tidal prism, as an indicator of active sedimentation or erosion, and as a management tool when paired with Escoffier's (1940) method of predicting inlet stability. There are many papers that have provided additional data, seeking to increase the explanatory power of the relationship by including littoral drift effects, river inputs, and so on (Byrne et al. 1980; Eysink, 1991; Gao et al, 1994; Gerritsen et al, 1990; Hume and Herdendorf, 1993; Jarrett, 1976; Mayor-Mora, 1977; O'Brien, 1969). Departures from "equilibrium" conditions have also been considered by Escoffier (1940), O'Brien and Dean (1973), and Kraus (1998).

2.3.1. The development of a universal tidal prism – inlet area empirical relationship

Within a tidal inlet system, the equilibrium cross-sectional area can be related to a number of independent and dependent variables. The independent variables include freshwater discharges, flood and ebb tidal durations, tidal prism, intensity of longshore drift, and sediment characteristics affecting sediment transport rates. The dependent variables consist of cross-sectional mean current speeds for flood and ebb tidal phases, width of the entrance channel, and the ratio of sediment discharge within the entrance to longshore sediment discharge (Goodwin and Cuffe, 1993). Despite the number of variables involved, the relationship in its general form is quite simple. It normally takes the form of an empirical equation of the form:

$$A_e = CP^n \tag{2.1}$$

Where A_e is the minimum cross-sectional area, P is the tidal prism, and C and n are empirically derived parameters (Battalio et al. 2006).

The first known published relationship between the cross-sectional area of a tidal inlet and the tidal prism were given by L.J. LeConte in 1905 for harbor entrances on the Pacific coast. Using standard notation, LeConte's relationship can be expressed as:

$$A = 3.3 \times 10^{-5} P \quad \text{for unprotected entrances} \tag{2.2}$$

$$A = 4.3 \times 10^{-5} P \quad \text{for inner harbor entrances} \tag{2.3}$$

Where A is the inlet cross-sectional area below mean sea level, in square feet, and P is the tidal prism corresponding to the spring range of tide, in cubic feet. LeConte only cited conditions at the harbor entrances at San Diego, San Pedro, San Francisco, and Humboldt, California. This relationship gained much more exposure in a later study by O'Brien (1931) who used a more extensive dataset to prove its validity. O'Brien proposed an equation of the form:

$$A_c = \alpha P_D^{\beta} \tag{2.4}$$

Where P_D is the diurnal tidal prism and A_c is the cross-sectional area of the inlet channel. In 1969, O'Brien reviewed this relationship in light of additional data that had become available since the initial study. Included in this review were data for 28 inlets, 9 on the Atlantic coast, 18 on the Pacific coast, and 1 on the Gulf Coast. Ultimately, O'Brien (1969) found that the best fit for unjettied inlets took the following form:

$$A = 2.00 \times 10^{-5} P \tag{2.5}$$

Johnson (1973), working with inlets on the Pacific coast, used hydrographic surveys available from the COE and National Ocean Survey (formerly USC&GS) navigation charts to measure entrance areas and bay surface areas. Using his measured surface areas, he calculated maximum tidal prisms for each of his sites. For six unimproved inlets, Johnson simply averaged the P_{max}/A values for these inlets and found:

$$A = 1.82 \times 10^{-5} P_{\max} \tag{2.6}$$

which is similar to the results of O'Brien. The majority of the prototype data was for Pacific coast inlets, most of which had been stabilized with dual jetty systems. This is also true of the studies of LeConte (1905) and O'Brien (1931,1969). Therefore, at this point it was clear that an empirical relationship existed between inlet area and tidal prism, but it was not certain how this relationship varied among inlets in different regions and with different amounts of stabilization.

Jarrett (1976) attempted to determine if inlets on all three coasts of the United States follow the same tidal prism-inlet area relationship, and also to establish what effect inlet stabilization has on this relationship. His analysis was more thorough than previous attempts. He used two separate methods to calculate tidal prism, and took into account the fact that tidal propagation within estuaries and lagoons varies based on site characteristics.

The majority of the tidal prisms computed by O'Brien and Johnson were determined by multiplying the surface area of the bay by a tide range at or near the entrance to the bay. This particular method does not account for phase and tide range differences that may exist for various locations within the bay and the resulting tidal prisms may be larger than in reality. The two methods that Jarrett employed varied in complexity, but each presumably gave better estimates of tidal prism than values acquired using average lagoon surface areas. Jarrett's "cubature" method takes into account the time required for a tidal wave to propagate through the inlet and into the bay, i.e., rather than assuming a uniform rise and fall of the tide over the entire bay, the cubature method segments the bay into subareas that have approximately the same "phase range". The other method employed by Jarrett involved obtaining inlet cross-sectional areas at current measurement stations from National Ocean Service (NOS) hydrographic surveys made at approximately the same time that the velocities were observed.

Ultimately, Jarrett established a form of the best-fit equation for 11 sets of data, including jettied and unjettied inlets on the Pacific, Gulf, and Atlantic coasts. A more detailed regression analysis was performed on each set of data and 95 percent confidence limits were established for the regression constants C and n. The fit to all the data proposed by Jarrett was:

$$A = 5.74 \times 10^{-5} P^{0.95} \qquad (2.7)$$

This relationship was found to predict smaller cross-sectional areas than measured values for Atlantic Coast inlets, and larger cross-sectional areas than measured values for the

Pacific Coast. In other words, for an equivalent tidal prism, Pacific coast inlets have smaller cross-sectional areas than their Atlantic Coast counterparts, which is an interesting finding. Many researchers eventually attributed this to differences in wave climates, but this theory was challenged by Bruun (1986). The differences between the curves for unjettied or single jettied inlets on the Atlantic and Pacific coasts could be caused by the differences in the computational methods used to determine the tidal prisms or they could be related to the differences in wave and/or tide characteristics that exist between these two coasts (Jarrett, 1976).

Although the expressions established by Jarrett are considered the best available empirical predictors for equilibrium cross-sectional areas, small inlets tend to exhibit equilibrium areas much larger than predicted by these tidal prism relationships (Hughes, 2002). This is especially true of modeling studies which make use of scaled-down physical models of tidal inlets (e.g. Mayor-Mora 1977). Byrne and Gammisch (1980) showed that the transition occurred in the range of inlet areas from 100-500 m^2. This type of deficiency is sometimes noted as a weakness of empirical methods, and the next section will show that further research later addressed this issue.

2.3.2. Recent advances in the Jarrett Relationship

Kraus (1998) suggested a process-based derivation of the prism-area relationship. He reasoned that at equilibrium, the rate of change of volume and hence area in the inlet must tend to zero. He derived an equation of the form:

$$A = \left(\frac{\alpha \pi^3 C_k^3 n^2 W_e^{4/3}}{Q_g T^3} \right)^{0.3} P^{0.9} \tag{2.8}$$

Where α and C_k are empirical coefficients close to unity, n is Manning's coefficient (assumed in this study to be 0.025), W_e is the width corresponding to the equilibrium area, Q_g is the gross longshore transport, and T is the tidal period**.**

The derivation by Kraus is process-based to the extent that the formulations used are valid phenomenological descriptions, but it does not prove the validity of a particular exponent that can be used universally. Although this relationship was found to have reasonable predictive power it was also found to be dependant of the form of the sediment transport equation or friction coefficient used in the derivation and so only provides a phenomenological proof of the area-prism relationship (Townend, 2005). Additionally, because the development is based on a balance between tidal flow rate and longshore sediment transport rate, applying Kraus's equation at sheltered locations having little or no longshore transport may become problematic because the inverse dependence on Q_g could make the cross-sectional area unrealistically large. Nevertheless, some believe that Kraus's equation should provide good equilibrium area estimates even when using approximate estimates of the gross longshore transport rate (Hughes 2002).

More recently, Hughes (2002) has derived an expression based on the concept of an equilibrium maximum discharge per unit width. This gives rise to an expression of the form:

$$A = 0.87\left[\frac{W^{1/9}}{\left[g(S_s - 1)^{4/9} d^{1/3} T^{8/9}\right]}\right] P^{8/9} \qquad (2.9)$$

Where S_s is the sediment's specific gravity, d is the median grain size diameter, W is the width of the inlet, T is the tidal period, g is the gravitational acceleration, A is the inlet cross-sectional area, and P is the tidal prism. Based on the exponents of each term, it is clear that the equilibrium cross-section area is strongly dependent on tidal prism and tidal period, with weaker dependence on channel width and gross longshore transport rate.
The formulation proposed by Hughes was found to be a good predictor and probably merits further development and use.

Many other studies have examined O'Brien's relationship, finding additional uses and warning about its limitations. Hume and Herdendorf (1988) wrote about the use of this relationship in New Zealand's inlet systems, noting that many researchers used the relationship in a qualitative manner to characterize an inlet that lies on the left side of the line as depositional in nature and one lying on the other side as erosional. Hume et al (1993) created a classification system for New Zealand tidal inlet systems based on geomorphological type and reformulated the regression of the relationship for each type. They found that it greatly improved the accuracy of the method. A recent study by Townend (2005) applied this theory to tidal inlets in the United Kingdom. He also found that it was useful to subdivide these systems by geomorphological type, and stated that there must be a transition between estuaries that are essentially unfilled geological basins to those that have filled with sediment over the Holocene.

Bruun (1978) advises that the Area-Prism approach is useful only as a "preliminary guidance for pre-evaluation of the conditions". The reason for this is that Area-Prism relationships are semi-empirical, and may not fully account for the many factors that affect inlet stability, including tidal prism, littoral drift, width/depth ratios, sediment grain size and bottom roughness. Hume and Herdendorf (1988) note that, ideally, characterization of inlet stability and predictions of inlet cross-section area based on area-prism relationships should be compared with assessments made by other methods, including analysis of historical morphometric data, application of conceptual models, use of a variety of empirical formulae, and employment of physical and numerical models.

2.4. Studies that introduced and developed the idea of inlet "stability"

According to Webb (1991), inlet stability refers to the long-term tendency for an inlet to remain open, and "unstable" inlets are inlets that experience periodic or long-term closures. Although much effort has been spent analyzing relationships that compare inlet geometry to the effective tidal prism, this type of an analysis fails to explain the behavior of small inlet systems that are chronically unstable, and prone to seasonal or sporadic closure. Several concerted efforts have been made to provide a general understanding of how inlets behave, regardless of size and stability. This section will describe some of the efforts that are relevant to this study.

2.4.1. Early Efforts to Characterize Stability: The Escoffier Method

Escoffier presented his theory on the cross-sectional stability of tidal inlets in 1940. Since then, his semi-empirical method has been used extensively and is still the principle way of evaluating the stability of inlets (Van de Kreeke, 1992). Escoffier's method for evaluating the stability of inlets recognizes that, on the basis of inlet hydraulics, the maximum velocity through an inlet increases with cross-sectional area A_c. With increasing A_c, the maximum velocity reaches a peak value for some intermediate value of A_c, and then decreases for larger cross-sectional areas. He argued that there is a stable maximum tidal velocity through the inlet that will scour out any excess sand carried into it by wind and waves. This velocity was assumed to be about 3 ft/s based on grain sizes in inlets. Plotting this horizontal line gives two points of intersection: one an unstable equilibrium cross section and the other a stable one (Dean and Dalrymple 2002).

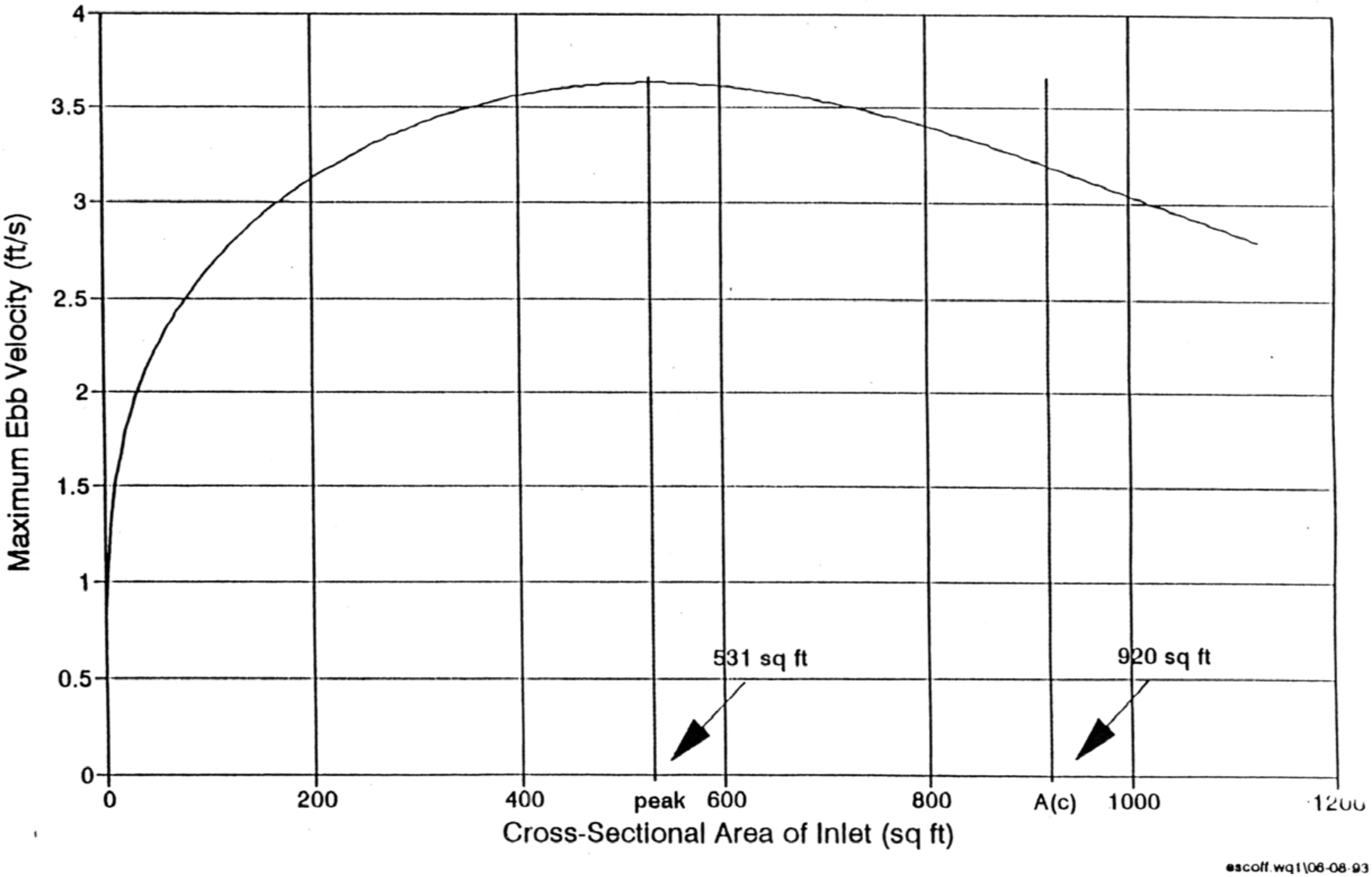

Figure 2.1. Escoffier Curve for the Russian River (Goodwin and Cuffe, 1993)

The basic assumptions underlying Escoffier's theory are:

1. The maximum current speed, $\breve{u}$, is a measure for the sediment transport capacity of the inlet currents.
2. Sand is carried into the inlet by littoral drift; when the maximum velocity, $\breve{u}$, equals the value $\breve{u}_{eq}$, referred to as the equilibrium velocity, the sediment transport capacity of the inlet currents is just sufficient to remove the sediment deposited in the inlet.

In general, the value of $\breve{u}_{eq}$ depends on the amount of sediment carried into the inlet, the sediment characteristics, the wave climate and the tidal period. The cross-sectional areas A_1 and A_2 in the stability diagram, corresponding to the intersection of the line $\breve{u} = \breve{u}_{eq}$ and the closure curve, are equilibrium flow areas; for these cross-sectional areas the maximum velocity is just large enough to remove sediment carried into the inlet by the littoral drift. A_1 represents an unstable and A_2 represents a stable equilibrium flow area. The inlet will reduce its cross-sectional area until it reaches the value of A_2. In a similar fashion it can be reasoned that for $A_1<A<A_2$, the sediment transport capacity is larger than that required to remove sediment carried into the inlet by the littoral drift and the inlet will increase its cross-sectional area until it reaches the value of A_2 (Van de Kreeke, 1992).

2.4.2. Different Perspectives on Stability Following Escoffier

O'Brien (1971) noticed that tidal inlets reach a dynamic equilibrium configuration when the littoral sand transported towards the mouth of the inlet by wave and currents is balanced by the scouring effect of currents in the channel. Based on this understanding and physical model tests, he proposed the following closure criteria:

$$S = \frac{P_W}{P_T} \tag{2.10}$$

Where: $$P_W = \frac{\gamma H_s^2 C_g}{2} \tag{2.11}$$

and $$P_T = \frac{h_r \gamma P}{bT} \tag{2.12}$$

P_W and P_T represent wave and tide "power" respectively, in units of force per unit length. Here, γ is the unit weight of water, H_s is the significant wave height, C_g is the group speed, h_r is the ocean tide range, P is the tidal prism, b is the width of the inlet, and T is the tidal period. S represents a non-dimensional index, which can be used to predict events in which inlet closure may be imminent. Although this method includes wave considerations, it is similar to Escoffier's method in that it does not explicitly account for sediment transport, which may be a potential weakness. It assumes that events classified by high waves can be associated with high rates of sediment transport in the vicinity of the inlet, which could cause closure. Despite its limitations, the O'Brien stability criterion explicitly accounts for the opposing forces of waves and tides and has been shown to predict inlet stability over the short-term due to time-varying conditions (Williams and Cuffe, 1993; Goodwin, 1996; Battalio et al., 2006).

Ideally, O'Brien's method requires moderately accurate wave measurements near the inlet, which are rarely, if ever, available. Johnson (1973) noted that this type of data is lacking for most sites, and instead proposed a simplified approach of comparing the estimated average annual deep-water wave power with the potential tidal prism. Johnson concluded that for a given wave power, there appears to be a tidal prism that must be exceeded if the inlet is to remain open. Johnson's method is very similar to O'Brien's in that it makes use of a closure parameter, in this case, called C_w, based on the ratio of wave energy and tidal energy. Johnson theorized that the inlet is stable, or at equilibrium, when this closure parameter is greater than or equal to some critical value:

$$\frac{C_W}{C_{Crit}} < 1 \quad \text{Inlet remains open} \tag{2.13}$$

$$\frac{C_W}{C_{Crit}} > 1 \quad \text{Inlet will close} \tag{2.14}$$

$$C_W = \frac{E_S T_P W_C}{P(2\eta_0)\rho} \tag{2.15}$$

Where C_w is the closure criteria parameter, E_s is the wave energy in foot-pounds per foot, T_p is tidal period, W_c is the width of the entrance to the inlet, P is the tidal prism, η_0 is the tidal amplitude in feet, and ρ is the unit weight of water. Since it is difficult to define the value of E_s, Johnson derived an alternative approach to the above equation using the annual deep water wave power, which is a measure of the total wave power reaching a certain part of a coastline based on deep water measurements of wave height and direction. He correlated this to the potential tidal prism, finding that for a specific value of the annual deep water wave power, there is a specific volume the potential tidal prism must exceed for the inlet to remain open. Johnson gave the results of his study in graphic form by plotting the annual wave power against the potential tidal prism and drawing a line to separate the inlets that have closed from those that remain open. Table 2.1 provides a list compiled by Goodwin and Cuffe (1993) using Johnson's data on several California lagoons. In Figure 2.2, Goodwin and Cuffe use Johnson's criteria to separate permanently open inlets from inlets that close.

Table 2.1. Tidal Inlet Characteristics for California Coastal Lagoons

Site	Location	Mean Tidal Prism (10^6 ft^3)	Annual Deep-Water Wave Power (10^{11} ft-lbf/ft/yr)	Closure Conditions
1	Smith River Estuary	24	303	Infrequent
2	Lake Earl	430	329	Frequent
3	Freshwater Lagoon	35	348	Always
4	Stone Lagoon	86	348	Frequent
5	Big Lagoon	240	348	Frequent
6	Eel River Delta	200	371	Infrequent
7	Russian River Estuary	78	200	Infrequent
8	Estero Americano	22	(200)	Frequent
9	Estero San Antonio	11	(200)	Frequent
10	Tomales Bay	1580	209	Never
11	Abbotts Lagoon	17	307	Frequent
12	Drakes Estero	490	26	Never
13	Bolinas Lagoon	200	117	Never
14	Pescadero	6.8	(200)	Frequent
15	Mugu, 1976	27	(100)	Frequent
16	Carpinteria	4.8[b]	(50)	Infrequent
17	Agua Hedionda, 1976	80	28	Never
18	Batiquitos, 1985	20	(30)	Frequent
19	San Dieguito, 1976	0.2	(30)	Frequent
20	Los Penasquitos, 1976	2	(30)	Frequent
21	Tijuana, 1986	12.6[b]	(100)	Infrequent
22	Bolsas Bay, 1874	38	(30)	Never
23	Anaheim Bay	47	(30)	Never
24	San Lorenzo River	3.69	(200)	Frequent

Parentheses indicate an estimate of deep-water wave power. [b] Indicates that tidal prism data is based on a large-scale topographic map. Modified from Goodwin and Cuffe (1993).

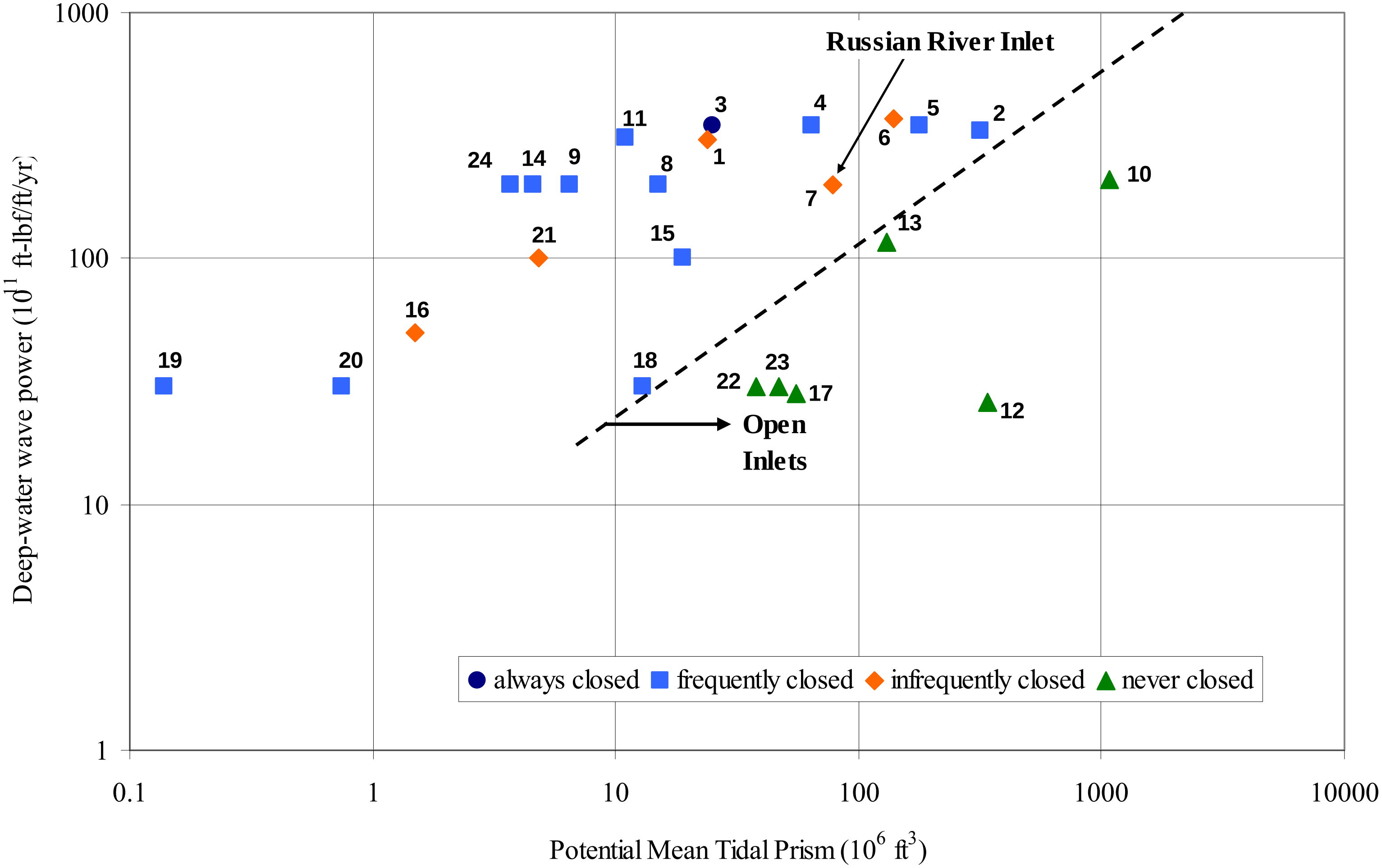

Figure 2.2. Johnson Criteria for closure of an inlet: Annual deep-water wave power vs potential mean tidal prism for several California lagoons. Modified from Goodwin and Cuffe (1993)

Applications of the O'Brien and Johnson methods can be improved with accurate estimates of wave and tide power. Many California lagoons and estuaries are partly sheltered from open ocean swell and seas, requiring adjustment of offshore wave data to represent wave conditions incident to the inlet (Battalio et al. 2006). Although finding adequate wave data near an inlet is difficult, there are ways to account for this lack of data if reliable measurements are available close enough to warrant the use of a wave refraction model. Such models are currently being constructed by the Coastal Data Information Program (CDIP), and have been used in stability analyses to account for the lack of nearshore wave measurements in some studies (e.g. PWA, 2001).

Bruun (1986) has argued that for tidal inlets on alluvial shores, it is not possible, in a scientific analysis, to separate flows from sedimentary aspects. Therefore, methods such as those of Escoffier (1940), O'Brien (1971), and Johnson (1973) which do not explicitly account for sediment transport may share a fundamental flaw. Bruun and Gerritsen (1960) introduced a parameter for examining inlet stability based on actual quantities of sediment available to the inlet:

$$\Omega/M \qquad (2.16)$$

Here, Ω is the tidal prism in units of cubic meters and M is the annual rate of littoral drift in units of cubic meters per year. They argue that the influence of the annual rate of littoral drift should play a role in inlet stability because inlets on coasts with high transport rates should have a different size than those serving similarly sized bays on a low-drift coast. Analysis of their method has shown that inlets with values of $\Omega/M > 300$ appear to be stable, whereas those with $\Omega/M < 100$ are more likely to be unstable and have shifting channels. Although this method appears to accurately differentiate between stable and unstable inlets, it is difficult to use for short term analysis, because actual measurements of sediment transport are extremely difficult to find and produce. Therefore, it is limited to use as merely a general indicator of the stability of an inlet at a timescale of years.

2.4.3. Inlet Stability in Systems With Freshwater Inflow

A common weakness shared by all of the aforementioned methods is the neglection of freshwater input to the tidal inlet. This limits the application of these theories to systems whose sole source of inlet currents is tidal influence. Many estuaries with significant river flows also experience closure, and accurate analyses of these systems will require either new methods or a modification of those mentioned above.

Escoffier and Walton (1979) re-derived Escoffier's (1940) stability analysis to include freshwater inflows to an inlet system. Their analysis provides solutions for inlet current velocities, and is meant to be used to construct Escoffier Curves, as was the case for Escoffier's previous work without freshwater inflow under consideration. Their method includes friction and inertia, and relies on estimates of inlet velocity to determine whether an inlet is stable or unstable. Ultimately, the computation of such results includes calculation of several lumped parameters used in one- and two-dimensional numerical models. Although this method may eventually prove to be accurate, the amount of time required to test it puts it out of the scope of the current study. Goodwin (1996) also attempted to account for this lack of consideration of river inputs. However, he did so by modifying O'Brien's (1971) model to include a "stream-power" term. This term does not follow from the classical definition of stream-power, and is dependant on the effective tide range as well as the discharge in the river:

$$S = \frac{\Phi_W}{\Phi_P} \tag{2.17}$$

$$\Phi_P = h_r g\left(\rho_s \frac{P}{T_r} + \rho Q\right) \tag{2.18}$$

$$\Phi_W = \frac{\gamma H_s^2 L}{2T_w b} \tag{2.19}$$

Here, all terms are the same as defined in O'Brien's (1971) method, with the addition of the deep water wave length (L), the deep water wave period (T_w), and the freshwater discharge into the estuary (Q). This method relies on gauged discharge for freshwater inflows into the estuary, and bypasses the lack of nearshore wave data by relying on deep water wave parameter measurements. Goodwin and Cuffe (1993) applied this method in an analysis of the Russian River Estuary, but until now it had yet to be tested with an extensive dataset. Several other approaches have been theorized, including efforts by Byrne et al. (1974), Mehta and Hou (1974), and Krishnamurthy (1979), among others.

2.5. Studies of Inlet Morphology, Configuration, and Closure Mechanics

Much work has been committed to the research of tidal inlet systems, but because the characteristics of these systems vary from site to site, general answers to some of the many questions about these systems have been hard to find. Various empirical relations describing the morphological properties of the inlet, ebb-tidal delta and back-barrier basin have been developed. These relations have recently been summarized by Buonaiuto and Kraus (2003). However, due to the complexity of physics involved, many aspects of inlet processes are still not fully understood (Elias et al. 2003). This section will provide a brief summary of some of the research efforts that have covered morphology, inlet area, effects of external forcing, sediment dynamics, and closure mechanics.

2.5.1. Morphological Considerations

The geometries of unjettied tidal inlets are subject to almost constant change, because tide, wave, and river conditions are also changing at any given time. In terms of the inlet cross-sectional area, these changes can be manifested as deepening or shallowing of the inlet mouth, or as widening or narrowing. FitzGerald and FitzGerald (1977) noticed that the depth of inlets can be significantly influenced by the relative importance of wave energy versus tidal energy. They found that micro-tidal coasts (tidal range less than 2m), where sand bodies are built more by waves than by tidal deposition (Hayes, 1975), inlets are relatively shallow with average depths of less than 6m (Jarrett, 1976). Goodwin and Williams (1991) argue that the size of the lagoon entrance depends on the balance between the longshore sediment transport and wave action closing the inlet and the degree of scouring caused by the freshwater outflow and the tidal prism. They note that local factors such as sediment characteristics, cobble bars, and other geologic features also affect the inlet channel configuration. Inlet geometry has great importance because it effects tidal conveyance and the magnitude of inlet currents, which scour out excess sediment. These currents are crucial for maintaining an open inlet because they induce shear stress on the bed of the inlet, which keeps sediment from depositing. Hibma et al. (2004) found that a minimum size of the channel is needed to exert a certain bottom shear stress, below which a channel is not able to remain open.

A series of studies by Wright and Coleman (1972, 1973) analyzed the behavior of systems with different types of tidal, wave, and river forcing. They found that when the tidal range and incident wave power are negligible or small relative to the strength of river outflow, river-dominated configurations result. In such cases, either inertia, turbulent bed friction, or buoyancy will tend to dominate. A later study by Wright (2006) discussed how in macro-tidal environments (maximum tide range greater than 4m, as defined by Hayes (1979)) where tidal currents are stronger than river flow, bidirectional currents redistribute river sediments, producing sand-filled, funnel-shaped distributaries and causing linear tidal ridges to replace the distributary mouth bar. Additionally, Wright noted that powerful waves promote rapid effluent diffusion and deceleration and produce constricted or deflected river mouths. These findings are all relevant to the current study, because at any given time any dynamic estuary-river system can experience different magnitudes of tidal range, wave power, or river flow.

There has also been a credible amount of work committed to the study of inlet morphology and channel configuration. In general, an excess of incoming sand causes an inlet to migrate. Part of the incoming sand is deposited on the updrift side of the inlet while the downdrift side erodes, and as a result the inlet is displaced downdrift (Escoffier, 1940). This transport of sand can continually change the shape and characteristics of an inlet. According to Galvin (1971), the configuration or geometry of inlets commonly varies, and these variations in updrift and downdrift shore configurations provide a basis for the classification of inlets. He created a classification system that groups inlets by their morphological configuration. FitzGerald and FitzGerald (1977) studied inlet asymmetry in several inlets in Chesapeake Bay, on the East Coast of the United States. They found that the degree of symmetry of the inlet channel is a product of three main factors: the meandering of the channel thalweg, the inlet shoreline configuration (Hayes et al 1970), and the dominant longshore transport direction. The "sedimentological characteristics" of the channel walls and bottom were also considered to be important factors. The tendency of inlet channels to lengthen under some conditions has also been observed. FitzGerald (1996) noted that commonly, as an inlet migrates, the channel connecting the inlet to the bay elongates, which increases frictional factors, attenuates tidal flow, and decreases tidal prism. This was observed in the modeling study of PWA (2004).

Several researchers argue that a full understanding of tidal inlet systems requires considerations of the ebb and flood tidal deltas. FitzGerald et al. (2002) note that sand transported into tidal inlets by tidal and wave-generated currents is moved seaward to ebb-tidal deltas by ebb currents or landward onto flood-tidal deltas by flood currents. They define ebb-deltas as short-term storage areas in the littoral transport regime at the seaward side of inlets which allow sand bypassing. They define flood-tidal deltas as features that develop on the landward side of the inlet and are longer-term repositories of sand that are usually not reworked until shoreline recession exposes these deposits to erosion on the seaward side of the barrier system. Ebb-tidal deltas develop at the mouths of tidal inlets and take on a variety of forms (Hayes, 1975) depending on how the sediment is reworked by tidal and wave-generated currents (Davis and Gibeaut, 1990). More frequently, modeling efforts are beginning to include these systems in their analysis. Hibma et al. (2004) recommend that the model region be extended to include the ebb-tidal delta when studying the evolution of tidal basins.

The ability of these ebb-tidal deltas to modify the effects of waves and littoral drift in the vicinity of inlet mouths makes them interesting features to study in tidal systems. As noted by Bagnold (1963), waves become increasingly important over the ebb-delta shoals, where the sediment transport involves interactions between the oscillatory motions of waves and any superimposed unidirectional current that governs the direction of the net transport. Gerritsen et al. (2003) note that most of the littoral drift will ultimately bypass the inlet by moving along the outer edge of the ebb tidal delta. The remainder of the drift will interact with the tidal flow through the inlet and ultimately either bypass the inlet or pass through the inlet channel to be deposited in the tidal bay. The overall morphology of the ebb-tidal delta is a function of the interaction of tidal currents and waves (Hayes, 1980). Probably the greatest advance made in understanding these features of inlet systems was made by Walton and Adams (1976) who showed a direct correlation between an inlet's tidal prism and the volume of sand comprising the ebb delta shoals.

2.5.2. Recent Considerations of the Mechanics of Inlet Closure

Closure of inlets is generally understood as a process in which sediment moves towards the inlet and blocks the currents that typically keep it open. Normally, inlets maintain a state of dynamic balance between these inlet currents and the arriving sediment, producing an equilibrium inlet geometry. However, an excess of sediment supply or a decrease in inlet currents can lead to closure. The mode of sediment transport is usually classified as "longshore" or "cross-shore", depending on the direction and origin of transport. Ranasinghe and Pattiaratchi (1998, 2003) define two mechanisms for inlet closure that differentiate between these two modes of sediment transport:

Mechanism 1- interaction between inlet current and longshore current

The tidal inlet interrupts the longshore current and thus the longshore sediment transport. As a result, a shoal will form up-drift of the inlet. The size and growth rate of the shoal will depend on the intensity of longshore sediment transport. In most cases a smaller shoal will also develop down-drift of the inlet (Oertel 1972; Hayes, 1975; Komar, 1976, 1996; FitzGerald, 1988, 1996). Bruun and Gerritsen (1960), Largier et al. (1992), and Gordon (1990) attribute the closure of tidal inlets to this mechanism.

Mechanism 2- interaction between inlet current and cross-shore sediment transport

This mechanism can dominate only if the inlet current is small (< 1 m/s) and would therefore operate in regions of low tidal range where the tidal prism is small. Under stormy conditions, sand eroded from the beach and surf zone is transported offshore resulting in the formation of a longshore bar at the breaker position. After the storms subside and long-period swell waves begin to dominate, sand stored in the offshore bar will be transported onshore**.** FitzGerald (1988), Hayes (1991) and Cooper (1994) attribute the closure of small inlets to this mechanism.

Many other studies investigate the nature of inlet instability and closure. The generally accepted theory states that the maintenance of an open inlet requires a dynamic equilibrium between tides, wave-induced sediment transport, and if applicable, freshwater inflow (e.g. Komar, 1996; O'Brien, 1971). The shape of the inlet, and the configuration of the interior and exterior deltas are influenced by the wave induced sand transport alongshore towards the inlet, and by the scouring action of tidal currents. At some level of intensity of wave-induced sand transport, this scouring action is overpowered by the sand transport, closing the inlet (O'Brien, 1971). A good review of the literature related to this issue and the relevant processes can be found in the Coastal Engineering Manual provided by the COE (2002).

2.6. Modeling and Field Studies

De Vriend et al. (1993) note that the complex behavior of tidal inlets and the interactions between several processes make the validation of morphodynamic models with data difficult. Even though each sub-model may have been separately tested, their combination forms a new system which may not provide convincing results. For this reason, modeling of tidal inlet systems has not yet reached the level of accuracy that other fields such as river or wave mechanics have. Accurate modeling of these complex systems may require field work in addition to numerical analysis, and cannot be achieved without an adequate understanding of how the many relevant processes (i.e. wave-induced currents, tides, river discharge) interrelate. Several important numerical modeling and field studies of unstable inlets are summarized in this section.

2.6.1. Numerical Models

Ranasinghe and Pattiaratchi (2003) have put forward perhaps the most comprehensive modeling study of inlet closure. They argued that a morphodynamic model capable of simulating seasonal inlet closure should include tidal currents (especially in the vicinity of the inlet entrance), wave shoaling and refraction (and diffraction in some cases), longshore transport processes, and cross-shore transport processes. Their study included both numerical modeling and field experiments. All field experiments were undertaken at Wilson Inlet, a seasonally open tidal inlet located on an embayed beach along the southwestern coast of Australia. A detailed description of model formulation, including a description of model strengths and limitations is given in Ranasinghe et al (1999).

A 3D hydrodynamic model, a wave transformation model, and a morphological evolution model were developed for this study. The computational domain is constructed as a finite difference grid. The HAMburg Shelf Ocean Model (HAMSOM) was used to obtain the near-bottom tidal current velocities and surface elevations required for the sediment transport calculations. The model is fully described by Backhaus (1985) and Stronach et al. (1993). A monochromatic wave transformation model, RCPWAVE, was used to obtain wave heights and directions, wave numbers, and breaker positions required for the sediment transport calculations. A wave decay function based on Dally et al. (1984) was applied shoreward of the breaker line to predict wave heights within the surf zone.

The morphological model developed in this study consists of three main modules: a wave-driven currents module, sediment transport module, and a bed evolution module. The wave driven currents module marked an advance in the field, because it included both longshore and cross-shore transport. However, the authors noted that a simultaneous resolution of longshore and cross-shore currents would only be possible via a fully 3D Navier-Stokes solver incorporating radiation stress terms, which they did not use because they felt that it was beyond the scope of the study. With the sediment transport module, cross-shore and longshore sediment transport rates were estimated using the "energetics" approach of Bagnold (1963). As the main aim of the study was to investigate the relative importance of cross-shore versus longshore transport processes in causing seasonal inlet closure, it was of primary importance to design the model such that cross-shore or longshore transport could be "switched off" when required. Finally, in the bed evolution module, the cross-shore and longshore sediment transport rates were vectorially added to give the total sediment transport rates. The sediment transport rates thus calculated were used to solve the 2D sediment continuity equation to obtain bed level changes.

To determine conditions under which longshore processes or cross-shore processes control inlet closure, simulations were undertaken with and without cross-shore processes for an idealized inlet located on a straight beach. With longshore transport only, they found that a large shoal builds up on the updrift side of the inlet, while a much smaller shoal grows on the downdrift side. The ebb channel is shifted downstream due to the build-up of the upstream shoal. The continued growth of the upstream shoal causes inlet closure. When cross-shore transport was also taken into account, offshore erosion and nearshore accretion was indicated along the entire shoreline and the inlet closed up mainly due to the continuous onshore movement of sand. However, the effect of longshore transport could be seen in the areas adjacent to the inlet (particularly on the updrift side) where the shoals build up more than in other areas. As the purpose of this part of the study was to identify when cross-shore processes are important when compared with longshore processes, no consideration was given to the effect of variations in tidal prism and streamflow.

The authors concluded that predominant swell wave conditions, weak and inconsistent longshore current, absence of channel infilling or spit progradation, and berm build-up during summer implied that onshore sediment transport may be the main process responsible for inlet closure at their site. However, when longshore and cross-shore transport were both taken into account, the closure of the inlet was still due to the growth of the updrift shoal caused mainly by longshore transport. Therefore, both processes may play significant roles in influencing closures at the site.

PWA (2004) conducted a study which drew upon O'Brien's (1971) method for predicting inlet instability. Conceptual models of natural closure and inlet breaching were developed to assist with adaptive management of Crissy Field, a small tidal lagoon located within San Francisco Bay, in California. Actions considered included mechanical breaching protocols and wetland expansion alternatives to reduce closure frequency for ecologic benefit. Battalio et al. (2006) later presented the details of the model used in this study.

The stability of the tidal inlet was examined for existing conditions as well as various enlarged wetland sizes by application of a Quantified Conceptual Model (QCM). The authors noted that the model is not a precise engineering tool that explicitly simulates the sediment transport processes. Instead, the QCM is based on simple stability criteria and easily computed parameters such as wave and tidal power as surrogates for complex sediment transport processes at the inlet. The conceptual model was quantified using field data collected at the site in order to develop a tool to predict closure and breaching of the inlet at Crissy Field. It is based upon the use of O'Brien's (1971) stability index to estimate the likelihood for closure and a breach criterion based upon water levels in the bay.

To overcome the need for nearshore wave measurements in O'Brien's (1971) method, offshore wave energy was transferred to nearshore values based on methods established in a previous study by PWA (2001). The approach uses a transformation matrix derived by comparing directional wave data measured at an offshore buoy outside of the bay and at Crissy Field, about 300 yards to the east of the inlet in water depth of 10 meters.

Coefficients from the transformation matrix are used to estimate nearshore wave heights from offshore conditions. This analysis required linear wave theory and the simplified representation of very complex transformations into a single ratio of wave heights. Details and limitations of this methodology are discussed in PWA (2001)

Low water (LW) elevation was set by the maximum thalweg elevation. Since the majority of the effective tidal prism is drained during the first half of the ebb cycle in the bay, tidal power at Crissy Field was computed by setting the tidal period (T) to 6.25 hours and taking the difference between higher-high (HH) and low water (LW) as the effective tidal range in the marsh. They also modeled the change in the elevation of the beach barrier after closure events. This is an important consideration, because the low point in the berm is where the inlet will form once it reopens, and such an analysis can be used to predict the height of waves or the amount of freshwater inflow needed to recreate the inlet. Closures during the storms of November 2001 – January 2002 were used to calibrate the simulated evolution of the beach barrier. As described earlier, the simulated beach barrier elevation is determined by the bay water levels at time of closure and increases if large wave activity continues while the inlet remains closed.

PWA (2004) found that inlet closures took place under a variety of conditions. Closures typically either occurred during events when moderate or high waves coincided with the neap tide range, or during events when high waves coincided with moderate or low tides and an inefficient channel configuration. They noted the importance of the channel configuration and discussed how different configurations can affect the stability of the inlet. As a conclusion they found that although the loss of energy available for keeping the inlet open was most strongly influenced by the smaller effective tidal prism, friction losses along an elongated inlet channel can also play a role.

2.6.2. Field Studies

Webb (1991) studied the stability of several Southern California tidal inlets. The objectives of his study were to analyze inlet morphologic response relative to process and material parameters and to compare temporal and spatial patterns of inlet morpho-dynamics at three small southern California tidal inlets**.** The 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.

The majority of this effort was devoted to field work. Topographic surveys were performed at low water during neap and spring tide events, and large wave and stream stormflow events. Cross-sectional measurements were made along transects across the inlet, with the transects spaced at regular intervals from the lagoon to the sea. Surface flow velocity was estimated by measuring the time taken for a float to travel 25 meters. Three measurements were obtained and their average was calculated. This average surface flow velocity was multiplied by 0.7 to estimate mean channel flow velocity, according to the method of Mehta (1988).

Wave and tide records were also analyzed to understand the conditions that may have led to closures that took place prior to the study. Webb (1991) noted that, historically, closures of the Tijuana River inlet have occurred only three times over thirty years prior to the study, always during winter or early spring. Wave data collected before and during these closure dates showed that waves were 1.3m or larger, and approached the shore from significant angles. The Tijuana River inlet remained open during high waves (3.0m) when other factors, such as stream stormflows and spring tides (2.5m range), maintained sufficient flow in the inlets to remove littoral sediment (Webb et al. 1989). 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. Although the tide may have been a dominant factor in maintaining stability in these inlets, stormwater inflows also played a significant role. Though stormflow discharges are low at the San Dieguito and Los Penasquitos inlets, they were found to be the major natural process for reopening these inlets once they are closed.

Webb noted that the morphodynamics observed at the study inlets illustrated the great complexity in measuring and isolating process-response relationships. He found it particularly difficult to capture important episodic events when relying on manual measurement techniques such as topographic cross-sectional surveys. He noted that it was for this reason that field measurements should be combined with numerical models in order to study important high magnitude/low recurrence frequency processes.

2.7. Russian River Studies

There have been a number of studies conducted in the estuary of the Russian River throughout its recent history. The emphasis in the studies has shifted notably over the past half-century. Initial studies investigated the feasibility of maintaining a permanently open mouth (e.g. Sonoma County Planning Commission, 1957). As the field of sediment transport began to develop, and as the usefulness of longshore sediment transport estimates for coastal engineering applications became known, several studies began to include estimates of the transport within the Russian River littoral cell, including those by Johnson (1959), Cherry (1964), Minard (1971) and de Graca (1976). Estimates of sediment transport in the river itself were also made. de Graca (1976) estimated that the total amount of beach materials discharged at the mouth of the Russian River, including both bedload and suspended load materials, amounted to approximately 267,000 tons per year. More recently, Simons, Li and Associates (1991) estimated that the bed material load passing through the lower end of the middle reach of the river near Hacienda Bridge (see Figure 2.3) is approximately 242,000 tons per year.

The study by Rice (1974) was the first to actually analyze the closure of the Russian River inlet from a scientific standpoint. He made several insightful observations, especially regarding the causes of the seasonal closure patterns of the inlet. For a span of two years, he analyzed inlet stability in terms of a ratio of water level range in the estuary to tidal range measured from the nearest ocean measurement station. He also took into account the freshwater discharge of the river. Ultimately, he noted that the majority of the closures took place in the months of October and November, and he argued that this was caused by a combination of moderate wave climate and low discharge in the river.

Goodwin and Cuffe (1993) conducted the only known research at the Russian River Estuary which analyzes the causes and effects of inlet closure since the study by Rice (1974). They conducted a six month hydrological and biological field monitoring program to identify the physical processes associated with the processes of inlet opening and closure, and to identify the influence of these physical processes in the estuarine ecosystem. The linkages between the physical and biological processes were combined with a knowledge of the flood damage to property to develop a management plan for the Russian River Estuary.

Goodwin and Cuffe (1993) surveyed the bathymetry of the Russian River Estuary during September, 1992. Thirty cross-sections of the estuary were surveyed from the barrier beach to the confluence with Austin Creek. Additionally, the barrier beach and inlet were surveyed on several dates, and several useful plots were produced, including a stage-storage relationship for the estuary. This study also predicted the stability of the inlet using Bruun and Gerritsen's (1960) parameter, as well as Goodwin's (1996) stability index which had yet to be published. The Bruun and Gerritsen (1960) analysis was used by referring to previous studies that had predicted longshore sediment transport rates for the littoral cell adjacent to the Russian River inlet. As expected, it indicated that the inlet is unstable and should experience closure. Goodwin's (1996) stability index appeared to exhibit high values prior to closure events that took place during the study, which would imply that it worked well as a predictor, but the dataset that was used was limited and it was unclear whether it could potentially be used as a management tool.

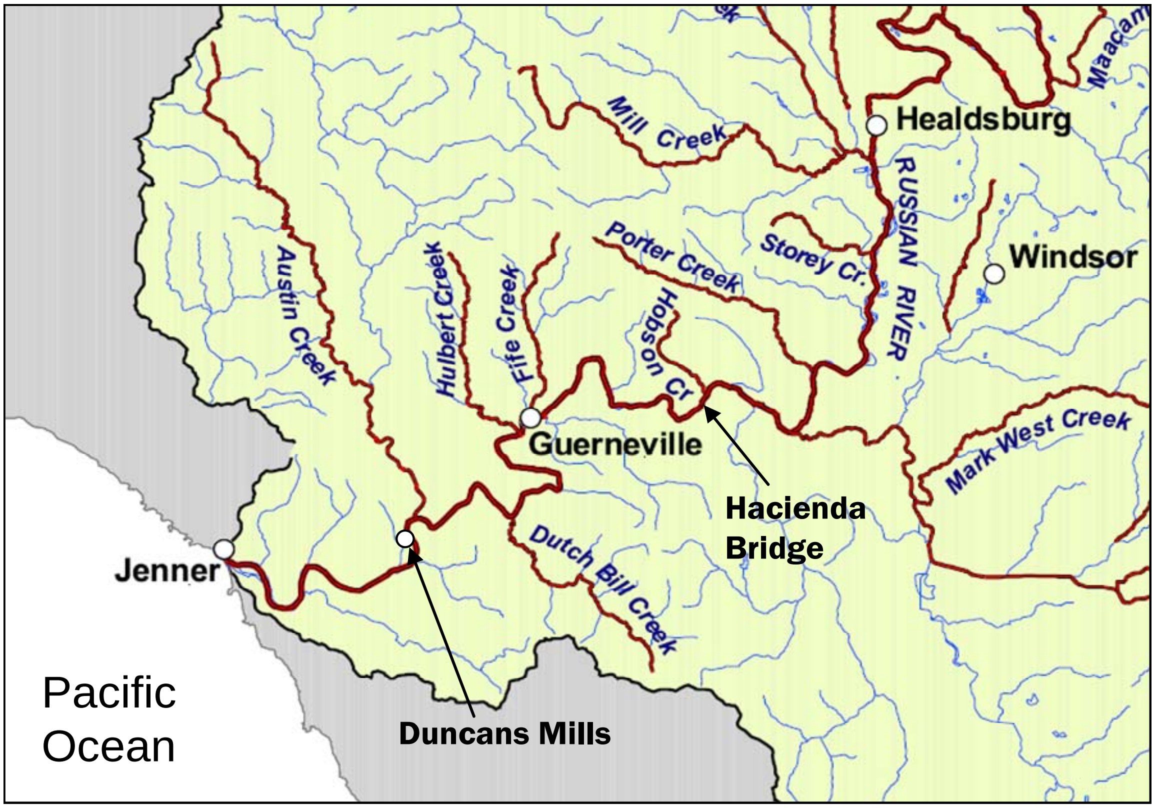

Figure 2.3. Abbreviated map of the lower portion of the Russian River watershed. <http://sotoyomercd.org/arundo/russian_river.pdf>

A particularly useful aspect of the study was the creation of an Escoffier Curve for the Russian River, which showed that the maximum ebb velocity at the inlet is approximately 3.7 ft/s and occurs at a cross-sectional inlet area of approximately 530 ft^2. The authors used the Jarrett relationship to calculate an equilibrium cross-sectional area of 920 ft^2 for the inlet. According to the authors, the Escoffier Curve demonstrates that as the area of the inlet channel is reduced from 920 ft^2 by wave action to about 250 ft^2, the ebb velocity is increased. Since Escoffier's theory suggests that the scouring action in the inlet channel is proportional to the maximum ebb velocity, an increase in the ebb velocity will increase the scouring in the inlet channel and the cross-sectional area will increase and move back towards the equilibrium value of 920 ft^2. However, if a wave storm decreases the inlet area to less than 250 ft^2, the maximum ebb velocity and scouring ability is reduced and the inlet area becomes smaller and smaller until closure occurs (Goodwin and Cuffe, 1993).

The authors made several conclusions about the behavior of the inlet:

1. Closure of the estuary occurred during both spring and neap tides, although there was a greater tendency for the inlet to close during neap or intermediate tide ranges. The timing of closure is therefore dependent upon tidal prism, river inflows, and wave conditions.
2. The estuary did not appear to close during the wet season months within the study period, implying that there is a critical river discharge above which the estuary will not close.
3. Closure could occur during neap tides with low wave energy, or spring tides with high wave energy. Therefore, it is necessary to evaluate the relative roles of tidal prism, wave energy, and river discharges in causing closure.

The first and third conclusions are particularly important, especially considering the similar result from the PWA study of the Crissy Field lagoon. Closure in these types of systems may take place even at spring tide levels if waves are particularly strong. While it is likely that there is a critical river discharge above which the estuary will not close, the statement that closure does not take place during the wet months of the year is an inference made from a very small set of data. Chapter 3 of this thesis will show that this assumption is wrong in some cases.

The environmental impacts of closure and opening of the inlet were also covered by Goodwin and Cuffe (1993). It was noted that the Russian River Estuary and the freshwater marsh on Willow Creek provide habitat and food for a substantially diverse fauna and flora which appear to have adapted to the limnological shifts occurring with periodic closure of the river mouth. Changes in the distribution and abundance of critical aquatic habitat occurred during closure and breaching events, but these changes did not have significant long-term impacts on the biological community as a whole.

The study by Goodwin and Cuffe (1993) was prepared in accordance with a work program developed by the Russian River Estuary Interagency Task Force to evaluate the impacts of artificially breaching the River mouth and to select a preferred estuary management program. The hydrological study and flooding assessment were conducted by Philip Williams and Associates Ltd. under the direction of Peter Goodwin. Ultimately, a management plan was developed that called for post-closure breaching of the barrier beach at particular estuary water levels. The main elements of the management plan include:

1. The barrier beach should be breached in the range +4.5 to +7.0 feet NGVD

2. Timing of artificial breaches is important during the spring and fall to assure the passage of aquatic invertebrates. During periods of prolonged estuary closure, additional artificial breaching in the range +4.5 to +7.5 feet NGVD may be warranted if the biological monitoring demonstrates a need.

The Sonoma County Water Agency currently oversees the majority of the studies and the mechanical breaching in the estuary, and is responsible for the manual breaching of the inlet. They have produced monitoring reports for the years 1996-2000 that track the biology and water quality of the system. More recently, they have committed to clarifying the relationship between inlet processes and changes in the local ecology. They published studies regarding the estuary fish and macro-invertebrates in 2004 and 2005, and a comprehensive report on environmental issues within the estuary (e.g. Martini-Lamb, 2005). Their work in this estuary is ongoing, and many more reports are anticipated.

Chapter 3. Predicting Inlet Closure In An Estuary Using Non-Dimensional Stability Indices: The Case Of The Russian River

Dane K. Behrens, Fabián A. Bombardelli, John Largier

Keywords: inlet stability, inlet closure, sediment transport

Abstract

Many tidal inlets experience closure every year. Researchers have studied this phenomenon for many years, but for the most part they have placed emphasis on systems without river influence. Many estuaries with significant freshwater inflow also experience inlet closure, but studies of this effect are not common. O'Brien (1971) developed a method which indicates the susceptibility of inlet closure based on the interaction of processes that promote and prevent closure at an inlet; however, this method only deals explicitly with wave and tidal processes. The current study introduces a term to account for river influence, similar to that of Goodwin (1996). The site of this study is the Russian River Estuary, in northern California. The dataset was obtained from field evidence donated by a resident who lives near the mouth of the river. This consists of over 20 years of recorded daily inlet conditions in addition to 17 years of daily panoramic photographs of the inlet. This dataset was paired with local tide, wave, and discharge measurements to test several methods for predicting inlet closure at the site. Ultimately, a method introduced in this study which accounts for wave, tide, and river influences provided the best results. When tested against the known closure record from 1999 to 2006, it predicted nearly 85% of closures to within 3 days of accuracy.

3.1. Introduction

Many embayments and estuaries along the US west coast (and elsewhere) experience closure of their inlet channel, an important feature that provides them with communication to ocean waters. With many systems this process takes place once per year and is a seasonal trait, although many others close and re-open many times in a given year. These closures result from wave-driven sediment transport and longshore littoral currents, and are typically prevented by inlet currents caused by tidal flows through the inlet (O'Brien, 1971). However, in many regions, tides are insufficient to provide inlet currents strong enough to prevent sedimentation and closure. Although river inflows may aid the tides and prevent closure by helping to flush out deposited sediment, local wave climates and sediment transport may still force the inlet to close. For example, at least 10 rivers in California experience either seasonal or sporadic closure each year (see Table 2.1). This is significant because closure of these systems greatly increases the likelihood of flooding of local property and drastically changes the water quality and tendencies for stratification of the embayment/estuary, which can have significant adverse environmental effects on the ecosystem. Despite the fact that inlets have been studied for more than a century, most research has focused on inlets in systems with little or no river flow, neglecting the major and important subset of estuarine inlet systems.

The morphological behavior of an inlet is a complex function of wave-driven sediment transport and inlet scouring caused by tidal variations and river flow (Komar, 1996). In general, the major processes balance, contributing to an equilibrium inlet configuration

(O'Brien, 1971). However, short-term variations in the wave climate or river inflow to the estuary can shift this balance and force an inlet to tend towards closure. An inlet that tends to remain open with full communication to the ocean is herein defined as "stable". An inlet which is tending to fill with sediment and close over time is defined as "unstable". A shift from a stable to an unstable condition can be manifested as sudden or gradual changes in inlet geometry, migration of the inlet, or in extreme cases, as complete closure and loss of conveyance to the ocean.

Existing theories that address inlet instability and closure vary in complexity and typically emphasize the importance of certain inlet processes while neglecting others. The methods put forward by Escoffier (1940) and Escoffier and Walton (1979) are probably the most commonly used theories for predicting inlet closure. These analyses use a relationship between inlet cross-sectional area and inlet velocities to help anticipate unstable behavior and closure, but neglect the influence of waves. The method of Bruun and Gerritsen (1960) assesses inlet stability in terms of a ratio of the net longshore sediment drift over the tidal prism of the lagoon. This method has been shown to accurately indicate long-term instability of certain inlets, but it relies on sediment transport rates, which are difficult to measure, and thus it is not feasible for use as a predictor of closure in the short term. Furthermore, this method neglects river inputs, and thus would not be suitable for estuaries with significant freshwater inflows.

A method introduced by O'Brien (1971) relates the respective energy fluxes of waves and tides to produce a non-dimensional parameter which indicates the susceptibility of an inlet to close. Although this method does not explicitly account for sediment transport, it presents a simple conceptual model of an inlet based on a balance of energy fluxes that cause and prevent closure. The limited use of this theory has shown that it may work well as short-term predictor of closures in systems without freshwater inflow (e.g., PWA, 2004) but it has yet to be tested as a tool for estuarine inlet systems where river influence is not negligible. Goodwin (1996) proposed a modification to O'Brien's method which adds consideration for freshwater inflows to an inlet system.

The objectives of this study are as follows: Firstly, test several inlet stability models to see if they can predict inlet closure in an estuary with significant freshwater inflows, using the Russian River inlet as a case study. Second, use these models to indicate the relevance of each of the major processes involved in either stabilizing or closing the inlet. Emphasis has been placed on predictive models presented by O'Brien (1971) and Goodwin (1996). Modifications to these models are proposed in this study and also tested. In Section 2, we discuss the characteristics of the study site. Section 3 covers the various aspects of the dataset that were donated or created in this study. Following this are sections summarizing the results and conclusions.

3.2. Study site

The site of the current study is the Russian River Estuary, located on California's Sonoma Coast. The source of flow in the Russian River is primarily rainfall during the months from October to April. The river and one of its tributaries, Dry Creek, are dammed and used as a source of water for agricultural, municipal, and recreational use. In addition to management of river resources within the watershed, California's mediterranean climate, with mild winters and little rainfall during the summer, leads to a strong seasonality of river inflows entering the estuary. Average annual discharge measured at a gauging station 11 miles upstream of the river mouth is 2060 ft^3/s, with discharges typically in the range of 100 ft^3/s during the dry summer months and as high as 90,000 ft^3/s during floods. According to the classification of Hayes (1979), the site is meso-tidal, with spring tidal ranges of approximately 2.5 meters. Also, this region of the California coast is classified as mixed diurnal, with two unequal peaks in ocean level each day. The local wave climate is very energetic, and both swell and seas are present at the site. Seasonally strong swell from the northwest and southwest are the dominant causes of beach building and erosion in the vicinity of the river, and are responsible for powering the littoral transport along the coastline.

Figure 3.1. Aerial view of Russian River Estuary, facing east

Figure 3.1 shows that the beach in which the Russian River inlet resides is small (roughly 1600 meters in length), and is bounded by headlands at either end. These conditions may suggest that the primary source of beach sediment is derived from the river itself and transported landward by waves, but the degree to which the headlands block wave-driven sediment transport parallel to the coast is not entirely clear, and it cannot be assumed that longshore transport is negligible in the vicinity of the inlet. The topography of the estuary limits the influence of the local tides, which propagate as far as seven miles upstream through a narrow canyon-like basin before they reverse in direction. The lack of surface area of the narrow basin severely limits the volume of water that can enter and leave the estuary in a given tidal cycle, and as a result, currents through the inlet are occasionally low enough for the inlet to become unstable. An average of ten closures occur every year, mostly during the months of September, October, and November, when low rainfall coincides with a seasonal resurgence in wave activity (Rice, 1974). Figure 3.2 illustrates a closure that took place during October of 2006. Although the closure habits of the inlet generally follow a seasonal pattern, it is not uncommon for the river to close during the winter or spring, during years of low rainfall. Closures typically last no more than two weeks before ponding of the estuary causes estuary water to overtop the barrier beach, but the Sonoma County Water Agency typically reopens the inlet manually to prevent flooding of local property before the inlet can reopen on its own.

Figure 3.2. Evolution of a closure event at the mouth of the Russian River. Photographs courtesy of Elinar Twohy.

3.3 Dataset

A daily pictorial record of the river mouth ranging from the years 1990 to 2006 was generously donated by a resident who lives in Jenner, California, near the mouth of the Russian River. Additionally, the resident provided a complete written record of historical inlet closures from 1984 to 2006. Figures 3.3a and 3.3b provide an illustration of this record of inlet condition. This remarkable set of data was used to test several inlet closure prediction methods, which will be discussed in the next section. Additionally, the photographic record was used to provide estimates of the inlet width for each day from 1990 to 2006. This was possible because the set of photographs show the inlet, a nearby jetty, and several rock outcroppings, all of which are visible in satellite images available from GoogleEarth (see figure 3.4). Distances measured between each of these visible objects were used to estimate the dimensions of the inlet for each day during the period of record.

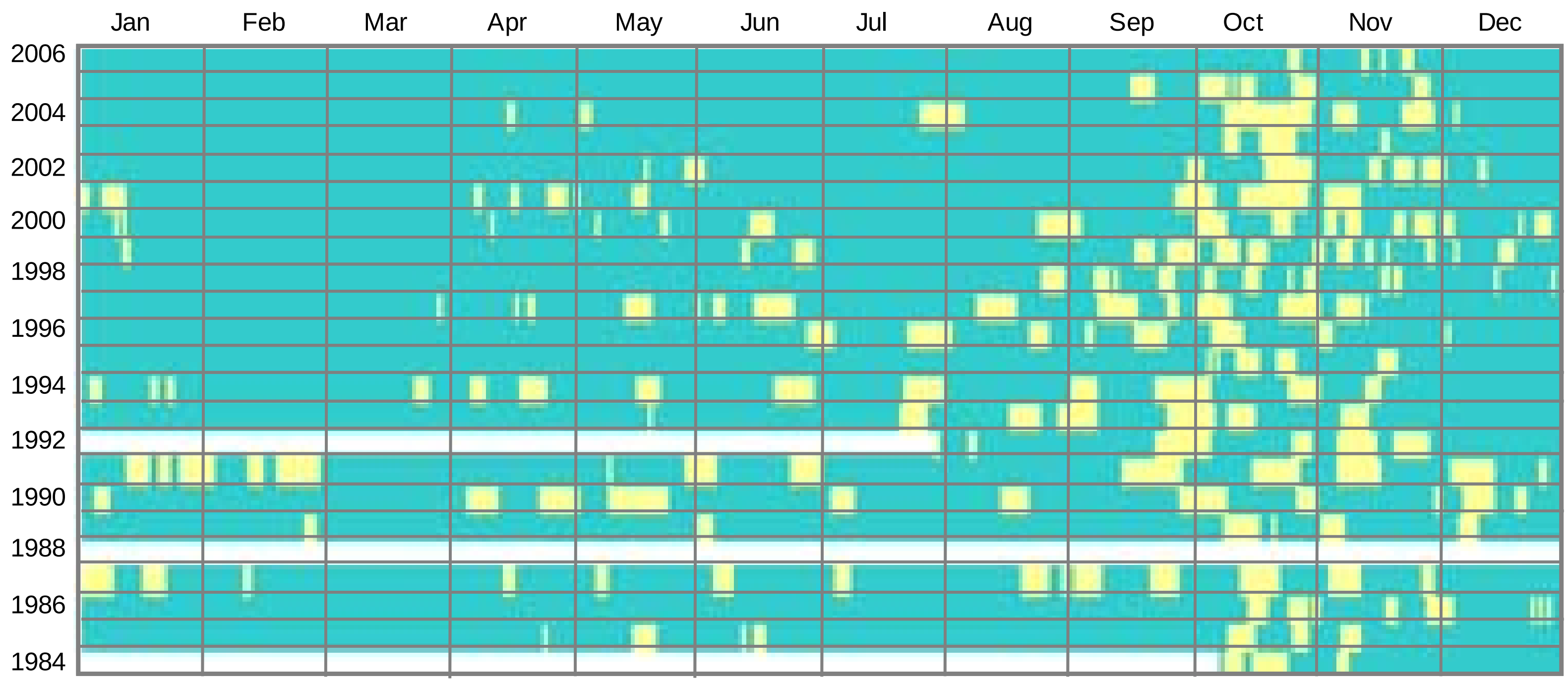

Figure 3.3a. Russian River inlet condition record

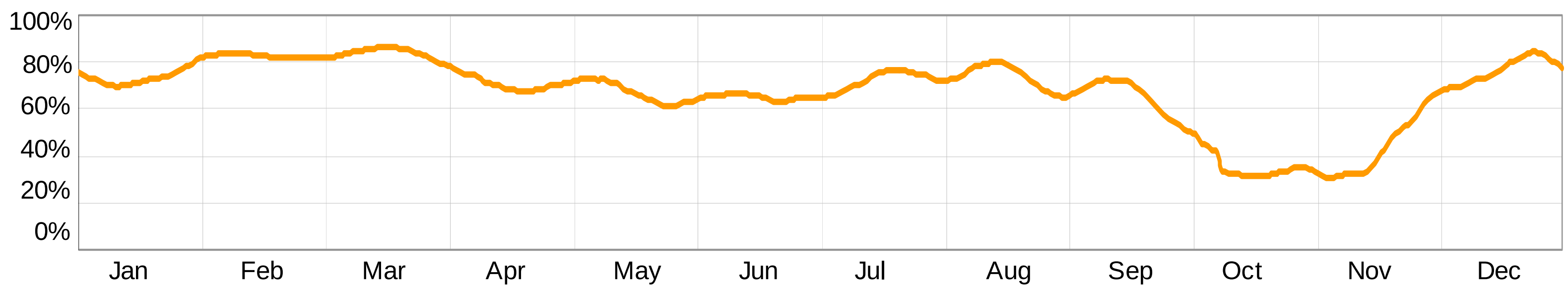

Figure 3.3b. Daily probability that the inlet is open

Figure 3.4. Barrier beach at the mouth of the Russian River. Available from GoogleEarth.

Wave measurements for the present study were obtained from the recordings of a buoy stationed 39 miles south of the Russian River mouth and 20 miles west of Point Reyes, California, at a depth of 550 meters. the Scripps Institute of Oceanography manages this buoy through its Coastal Data Information Program (CDIP), providing spectral wave data. Estimates of significant wave heights near the river mouth were calculated using a transformation matrix provided by CDIP. This method was also employed in the study by PWA (2004). A wave refraction model can calculate significant wave heights at the vicinity of the Russian River using the wave spectra measured at the CDIP Cordell Bank buoy. The end result is a matrix of coefficients which can be used to calculate wave heights at the Russian River based on incoming wave spectra measured at the deep-water buoy. This analysis uses wave theory and the simplified representation of very complex transformations into a single ratio of wave heights. Details and limitations of this methodology are discussed in PWA (2001). The shallow water approximation was used to account for the group velocity of the incident waves:

$$C_g = \sqrt{gh} \tag{3.2}$$

Here, C_g is the group velocity of the incident waves, g is gravitational acceleration, and h is the shallow water depth, taken to be the depth at the end of the inlet adjacent to the ocean. A depth of two meters was assumed, which is consistent with measurements made by Goodwin and Cuffe (1993) at the mouth of the Russian River. Figure 3.5 gives an example of the seasonal difference between deep-water wave measurements and near-shore wave estimates.

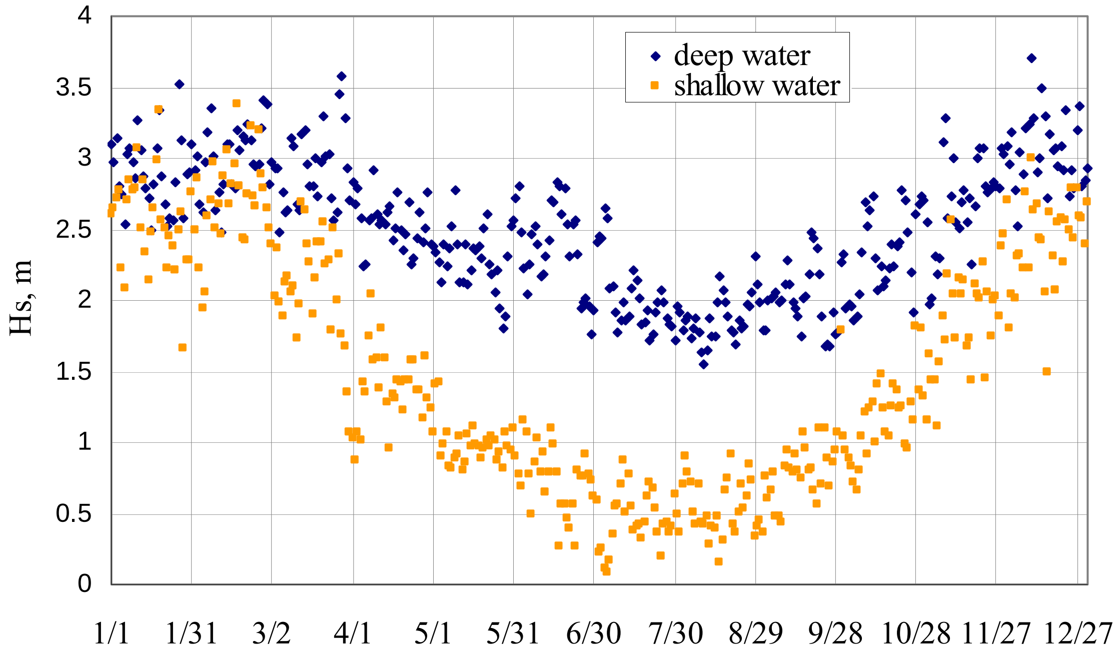

Figure 3.5. Comparison of deep-water measurements and shallow water estimates of significant wave heights, for average daily conditions over the period 1996-2007

Tide measurements were obtained from the National Data Buoy Center (NDBC) Bodega Buoy, which is located 18 miles south of the river mouth. Measurements of river discharge were found from the archives of the California Data Exchange Center (CDEC) for the Hacienda Bridge measuring station, located roughly 11 miles upstream of the mouth. Additionally, the Sonoma County Water Agency provided records of estuary water level (measured above the NGVD 1929 datum) for the years 1999-2006. The expected tide range in the estuary was determined by the higher high (HH) water level in the bay and the low water (LW) elevation, which is set by the maximum thalweg elevation of the inlet channel. Tide power was computed by setting the tidal period to 6.25 hours, which is the time of progression from HH to LW in the estuary, and by taking the difference between HH and LW as the effective tide range. The tidal prism of the estuary was estimated by multiplying the effective tide range by an average value of the estuary surface area provided by Goodwin and Cuffe (1993).

The wave, tide, and discharge data, as well as the record of closures and inlet width, overlap in the period from June 17, 1999 to December 31, 2006. The inlet closure prediction models analyzed in this study were tested in this length of time, in which 66 closures occurred. The availability of a reliable record of inlet closure, and the creation of a continuous record of inlet width, provide substantial advantages over previous studies regarding inlet stability. The availability of nearby wave, tide, and discharge measurements are also very fortunate.

3.4. Methods

O'Brien's non-dimensional approach to inlet stability was chosen for analysis in this study for the following reasons: (1) Computationally, it is much simpler than the more commonly used method of Escoffier, (2) it quantifies stability of an inlet at any time scale necessary, which is an advantage over the method of Bruun and Gerritsen, (3) it can easily be modified to represent inlet stability in systems with significant freshwater inputs, and (4) prior use of this method (e.g. PWA, 2004; Battalio et al. 2006) has shown that it can be accurate.

The method introduced by O'Brien (1971) was used during the 1990s in a study conducted by PWA (2004) of a small tidal inlet system called Crissy Field, in the San Francisco Bay. They applied O'Brien's theory to recreate a two-year record of closure at the site as an alternative to developing a computationally taxing numerical model. Their objective was to investigate possible lagoon expansion scenarios at their site and to analyze the possible effects of these expansions on the stability of the inlet. The results were considered adequate for planning purposes, and verification and improvement of the model through continued application at several inlets was proposed. A few reasons why O'Brien's method may have worked well in this case are the facts that Crissy Field has negligible freshwater inflow and a straight barrier beach with no headlands or irregular topography to complicate the longshore drift of sediment in the vicinity of the inlet.

O'Brien (1971) made the assumption that inlets reach a dynamic equilibrium based on a balance of the processes that promote and prevent closure. The stability of an inlet is defined here as a ratio of the energy fluxes of these processes:

$$\text{Stability} = \Phi = \frac{\sum P_{closure}}{\sum P_{opening}} \qquad (3.1)$$

Equation 3.1 defines inlet stability as a non-dimensional number (referred to herein as a "stability index"), which indicates the susceptibility of an inlet to close. When used as a management tool, a threshold value of the stability index must be set. In theory, whenever the stability index rises above this threshold, the risk for imminent inlet closure becomes high. The components that contribute to this index are listed in Table 3.1, and Figures 3.6a and 3.6b provide an example of how this type of model responds to changes in each of their intensities. O'Brien only considered systems that had no river influence, and formulated this index as a ratio of wave and tide power. Wave power is the energy flux of incoming wave groups and is proportional to the square of the incoming wave height and to the velocity. Tidal power represents the rate at which the potential energy of the water flushed through the inlet is spent during a tidal cycle. O'Brien introduced a coefficient (F) to account for the fraction of tidal power used to compensate for friction and velocity head loss. For this study, F is assumed to be equal to unity.

Goodwin (1996) modified O'Brien's stability index to include a term for stream power. This term is somewhat unorthodox in that it replaces the slope from the classical definition of stream power with a ratio of tide range to inlet width. Both Goodwin and O'Brien used phase velocity of waves rather than group velocity in calculating wave power. The earliest use of Goodwin's model took place during a study conducted by Goodwin and Cuffe (1993), which helped form the current management practices at the estuary of the Russian River. Goodwin was unable to test his theory extensively during the study, however, and its applicability has not yet been proven prior to this study.

Table 3.1: Components of the Stability Index

	$P_{closure}$	$P_{opening}$	
	Wave Power	Tide Power	Stream Power
O'Brien (1971)	$\frac{\gamma b L_0 H_0^2}{16T_w}$	$\frac{\gamma F h_r P}{T}$	--
Goodwin(1996)	$\frac{\gamma b L_0 H_0^2}{16T_w}$	$\frac{\gamma h_r P}{T}$	$\gamma h_r Q$
PWA (2004)	$\frac{\gamma H_s^2 C_g}{2}$	$\frac{\gamma h_r P}{bT}$	--
Current Study	$\frac{\gamma H_s^2 C_g}{2}$	$\frac{\gamma h_r P}{bT}$	γQS

The variables listed above are defined as follows: γ: Unit weight of water (kg/m^3); b: inlet width (m); L_0: deep-water wavelength (m); H_0: deep-water significant wave height (m); T_w: deep-water wave period (s); F: fraction of tide power needed to account for energy losses (dimensionless); h_r: tide range (m); P: tidal prism (m^3); T: tide period (s); Q: river discharge (m^3/s); Hs: shallow water significant wave height (m); C_g: wave group speed (m/s); S: bottom slope (m/m).

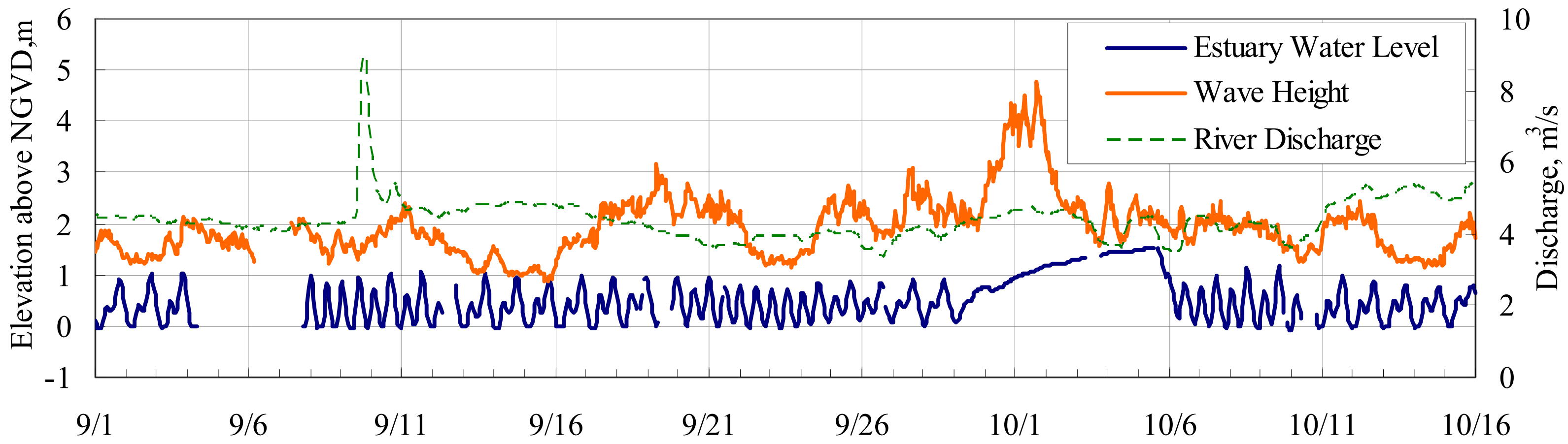

Figure 3.6a. Russian River discharge, deep-water wave height, and estuary water level during the year 2002

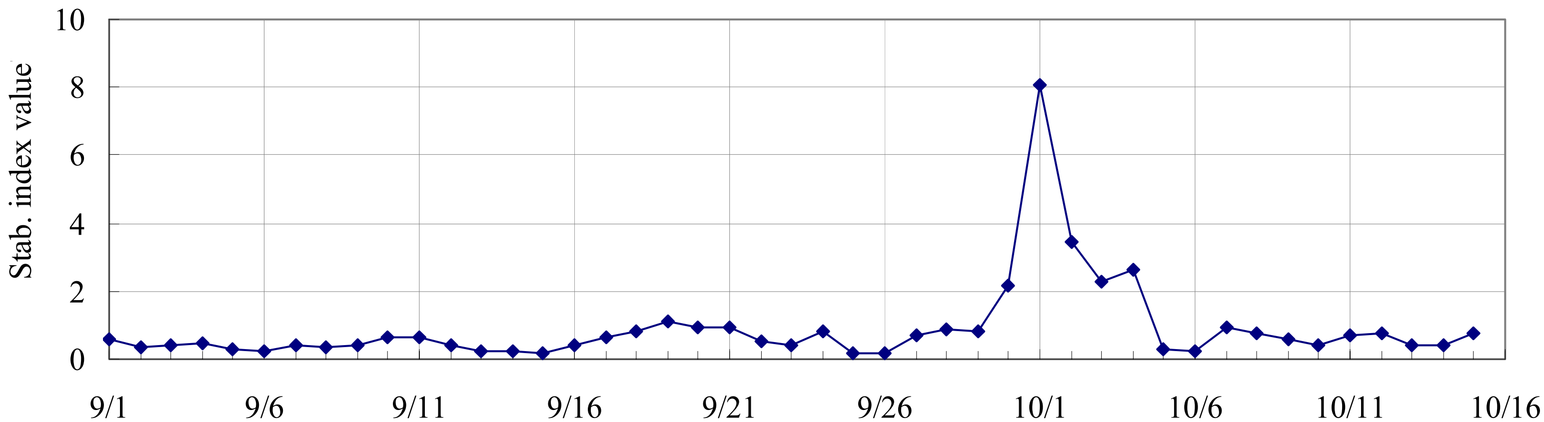

Figure 3.6b. Stability index, calculated using Proposed Method 3 for the year 2002

In addition to the methods of O’Brien and Goodwin, three additional methods are tested in this study. These are newly proposed methods introduced here to provide possible alternatives for predicting inlet stability. They are listed as “proposed methods” in Table 3.2. Proposed Method 1 is a non-dimensional index that only accounts for wave power and stream power. Tidal power is neglected here in order to show whether or not it is necessary in analyses of estuarine inlets with moderate river inflows. Proposed Method 2 also neglects tidal influences, but it accounts for wave and river influences differently than as defined above. Although this index is also non-dimensional, wave influence in this method is independent of wave speed, unless several assumptions are made: (1) the shallow-water approximation for group speed can be used, and (2) wave height is roughly equivalent to the depth at the inlet mouth. When these assumptions are applied, this method is equivalent to Proposed Method 1 without the coeffiecient of 1/2. Finally, Proposed Method 3 is similar to the method put forward by Goodwin; however, the classical definition of stream power is used, and wave power is calculated using wave group velocity rather than phase velocity. This method requires an estimation of the bottom slope (S) along the inlet channel. For this study, it was assumed that S = 0.001.

Table 3.2. Models Tested

Method	Expression	Advantages	Disadvantages
O'Brien (1976)	$\Phi = \frac{P_{wave}}{P_{tide}} = \frac{\left(\frac{\gamma H_s^2 C_g}{2}\right)}{\left(\frac{h_r \gamma P}{bT}\right)}$	• Has been proven to work for a tidal inlet with negligible river inlow (PWA, 2004)	• Doesn't account for river influence
Goodwin (1996)	$\Phi = \frac{P_{wave}}{P_{tide} + P_{discharge}} = \frac{\left(\frac{\gamma H_s^2 C_g b}{2}\right)}{\left(\gamma h_r \left(\frac{P}{T} + Q\right)\right)}$	• Includes stream power term to account for river influence	• Stream power is dependant on tide range • "Potential" tidal prism and tidal range are used, neglecting actual values which may vary due to sedimentation in the mouth
Proposed Method 1	$\Phi = \frac{P_{wave}}{P_{river}} = \frac{\left(\frac{\gamma H_s^2 C_g}{2}\right)}{\gamma QS}$	• May be more applicable for river-dominated inlets than methods with tidal considerations	• Doesn't account for tides, which can vary in influence due to seasonality of river flow
Proposed Method 2	$\Phi = \frac{g^{1/2} H_s^{5/2}}{QS}$	• Takes into account wave action without requiring measurements of wave group speed	• Doesn't account for tides, which can vary in influence due to seasonality of river flow
Proposed Method 3	$\Phi = \frac{P_{wave}}{P_{tide} + P_{discharge}} = \frac{\left(\frac{\gamma H_s^2 C_g}{2}\right)}{\frac{h_r \gamma P}{bT} + \gamma QS}$	• Includes stream power term to account for river influence • Stream power is not dependant on tide range	• Requires estimate of group speed • Requires estimate of inlet channel slope

Several assumptions were necessary to predict closure events at the Russian River. They can be summarized as follows:

1. Wave action causes the transport of sediments that eventually close the inlet.
2. Deposition of suspended sediment causes the majority of closures, rather than onshore movement of sandbars.
3. Wave, tide, and stream energy fluxes are the dominant processes affecting closure. Inlet stability can be conceptualized as a combination of these components, and other processes (e.g. seepage, evaporation, etc.) can be neglected.
4. The transition from an open inlet to a fully closed inlet lasts no more than five days.

The last assumption is a necessary feature of an O'Brien-type stability index. In order for such a tool to work properly, closures must occur almost instantaneously whenever the stability index reaches values that indicate that closure is imminent. Otherwise, the model has little predictive ability

The models tested in this study can indicate increased probabilities of imminent closure events. Inevitably, the success of this type of model will depend on where the stability index threshold is set for each particular system. Because the models rely on a ratio of wave energy flux to the energy flux of tidal and fluvial forces, any high wave event, low tide, or lack of river discharge will cause the stability index to indicate a change in the probability of closure. Analysis of wave, tide, and river data has shown that there are many events that occur every year that would seemingly cause closure, yet closures only take place when low discharge and low tides coincide with at least moderately high waves. In general, model predictions which correctly predict actual closure events are accompanied by very high stability index values, whereas incorrect predictions are accompanied by much lower values. This is not always the case, however, and predicting all the possible closure events requires adjustment of the threshold. Figure 3.3 provides an example of this. Setting the threshold high may allow the model to predict several of the closures without producing many predictions in error. Setting the threshold low will provide the maximum possible number of correct predictions for each model, but it also produces many incorrect predictions. Ultimately, maximizing the accuracy of these models and minimizing the number of incorrect predictions requires either: (1) a sizeable dataset which can be used to find the optimal threshold setting, or (2) an understanding of the closure habits at a particular site based on measured wave, tide, and discharge conditions. Since this type of analysis greatly simplifies the phenomenon of inlet closure and neglects many processes, it may not be possible to predict the majority of the closures without also predicting several closure events in error.

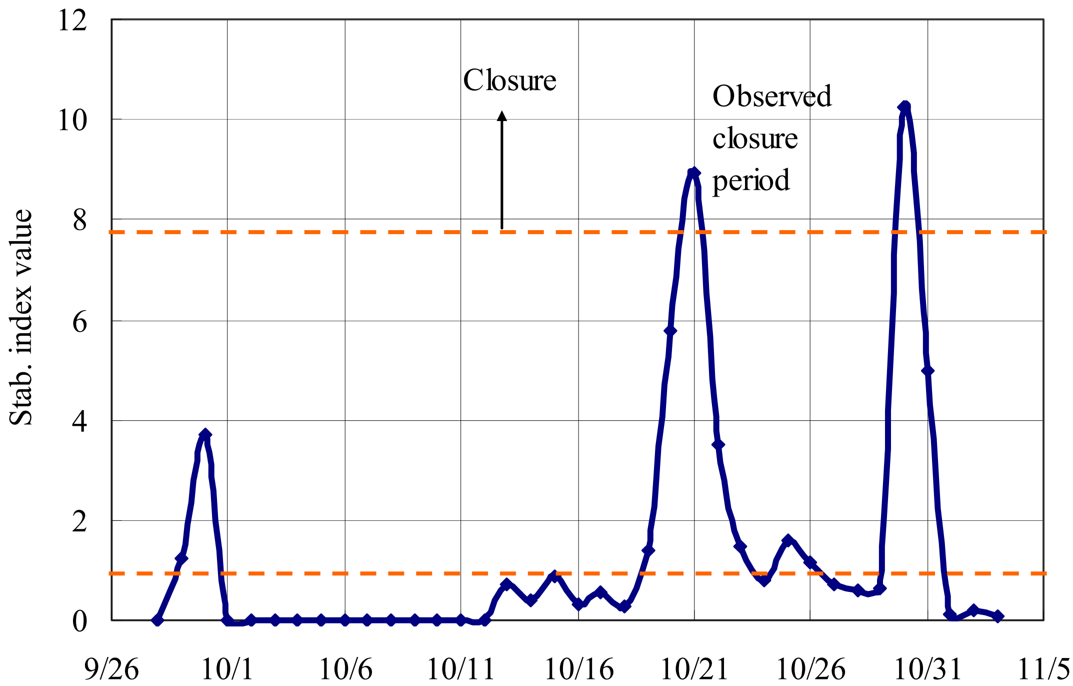

Figure 3.3. Stability index from Proposed Method 3 during the year 2002. Colored bands represent periods of closure. Dashed lines are possible thresholds.

In order to find a boundary of conditions that can lead to inlet closure, the estuary tidal range and river discharge for the days prior to each closure were plotted together on Figure 3.4. A key point here is that the tidal variations within the estuary are different from tidal variations measured offshore. Often, the inlet channel elevation will change in response to excess sedimentation or scouring, effectively changing the ability for tidal fluctuations on the ocean side of the inlet to propagate into the estuary. Several observations can be made from this figure. While tidal fluctuations on the ocean side of the inlet vary from 1.0-2.7 meters, most closures don't take place at this site unless sedimentation in the inlet significantly decreases the volume of tidal waters that reach the estuary for at least one day. Additionally, there appears to be a minimum discharge for which closures will not occur.

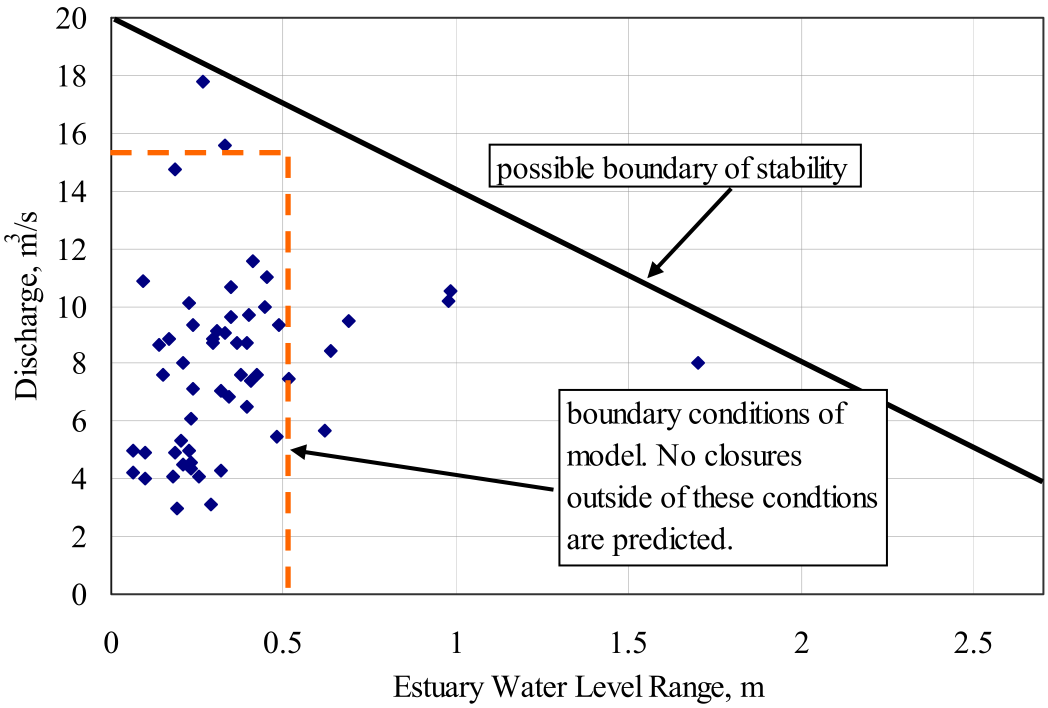

Figure 3.4. Tidal variations and discharge within the Russian River Estuary one day prior to closure events from 1999 to 2006

Both the discharge and the tidal fluctuations in the estuary contribute to inlet velocities which can prevent sedimentation from occurring in the inlet channel. The river and tides play a joint role in opposing wave-driven sediment transport and keeping the inlet stable, but if one or both of these contributors declines, the probability of closure greatly increases. A possible boundary of stability was drawn on this figure to indicate the joint magnitude of tide range and river discharge needed to produce sufficiently strong inlet currents to prevent closure. The observations made using this plot can be summarized as follows:

1. River discharges greater than 15 m^3/s provide enough inlet velocity to prevent the majority of closures
2. 85% of closures occurred when the tide range within the estuary was reduced to 0.5 meters or lower.

Each model was run using the daily tide, wave, and discharge measurements for the study period. To improve accuracy in accordance with the observations from Figure 3.4, no predictions of closure were made when discharge was above $15m^3/s$ or when the tidal range in the estuary was greater than 0.5 meters. The stability index threshold was varied so that three separate cases could be formed for each model: (1) the maximum number of correct predictions for each method was produced by setting the threshold to a very low value. (2) The threshold was adjusted so that each model produced no more than 10 incorrect predictions of closure for the study period (3) The threshold was adjusted so that each model produced no more than 20 incorrect predictions of closure for the study period. Cases (2) and (3) were necessary for several reasons. First, setting the threshold to limit the number of incorrect predictions indicates the usefulness of each of the methods as management tools at an unstable inlet site. It may not be feasible to use a method for predicting closure if it produces a large number of incorrect predictions, even if it also predicts the majority of the actual closures that take place. Second, several of the methods produced similar amounts of correct predictions, but varied in the amount of errors produced. Without limiting the number of errors, it would be unclear which methods were more accurate.

3.5. Results and Discussion

Figure 3.9 shows the accuracy of each model in reproducing the closure record for the study period. O'Brien's method did not perform well, which was expected because it does not account for river influence. Surprisingly, Goodwin's method also performed poorly. This may be due to the fact that Goodwin's stream power term is dependant on tide range. This would also explain the similarity of his results with those found for O'Brien's method, which only accounts for wave and tide influence. Proposed Methods 1 and 2 produced surprisingly different results. This is interesting because the shallow water assumption was used in both cases, leading to the simplification listed in Table 3.3. The large difference in results between these two methods may indicate the importance of river influence in the Russian River Estuary. This is evident because Proposed Method 2.

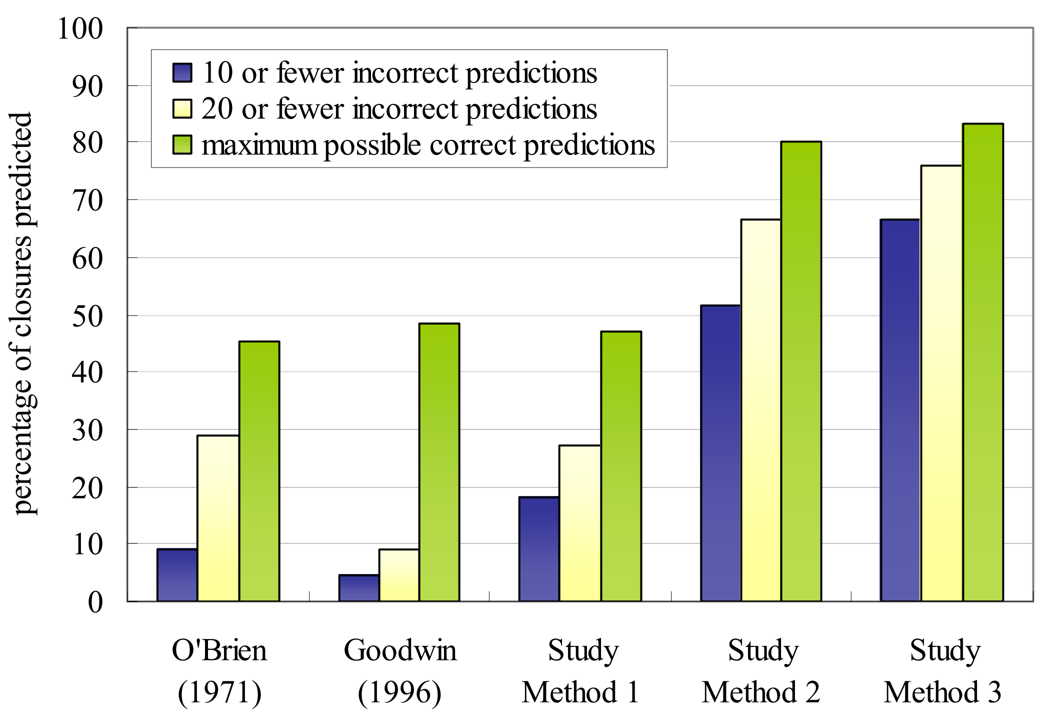

Figure 3.5. Comparison of results from predictive models. Predictions within 3 days of actual closure dates are considered correct.

is essentially the same as Proposed Method 1, but with a coefficient that doubles the stream power. If this analysis is extended to other estuaries, it may therefore be necessary to calibrate the model by adjusting the strength of each term. Proposed Method 3 produced the best results, which indicates that it is correct to account for tidal influence, despite the presence of significant fluvial input to the system. Tidal variations remain nearly constant throughout the year, while river discharge varies greatly. Tides become increasingly important during months of low river flow, and it is possible that during this time the system becomes similar to a tidal embayment such as those considered by O'Brien (1971) during his analysis. According to the results shown in Figure 3.9, with an average of ten closures each year, Proposed Method 3 correctly predicts eight closure events and produces one incorrect prediction each year.

Closures occurred during both spring and neap tides. This was expected and suggests that tidal influence alone is insufficient to maintain an open inlet at the study site. The same result was found by PWA (2004) at Crissy Field and in the earlier study conducted at the Russian River Estuary by Goodwin and Cuffe (1993). Figure 3.6a indicates that closures are more frequent during the spring and autumn months than during the summer. Although the river is weakest during the summer, the inlet remains stable because the intensity of waves also decreases. The wave intensity progressively increases during the autumn, but the slow rise in discharge during this season is inadequate to match the strength of the waves and prevent closure.

3.6. Sensitivity analysis

Since Proposed Method 3 produced the best results, sensitivity analyses were focused on the effects of changing certain variables within this particular method. It is expected that the sensitivity of this model to changes in its variables are similar to the sensitivities of the other models discussed in this study.

When the stability index of one of the methods indicates that a closure is imminent, the actual closure may still take several days to occur. In reality, closure events are not instantaneous, but rather slow processes which may take days or even weeks to form in some cases. Particularly high waves or low inlet currents may increase the rapidity of a closure, but a transition from an inlet with full conveyance of ocean tides to the estuary to a closed inlet with no conveyance takes more than one day. Therefore, it is difficult to create closure predictions that are accurate to within five days or less of the actual date of closure, because the rate of closure varies depending on the intensity of the incident waves, tides, and river flows, which all vary with time. The results presented in Figure 3.9 were formulated by only allowing predictions within three days of the actual closure date to be considered “correct”. The accuracy of the model changes slightly when the range for “correct” predictions shifts. This is shown in Table 3.4.

Table 3.3. Comparison of Proposed Methods 1 and 2 before and after shallow water assumption

	Before shallow water assumption	**After shallow water assumption**
Proposed Method 1	$\Phi = \frac{g^{1/2} H_s^{3/2}}{QS}$	$\Phi = \frac{H_s^2 C_g}{QS}$
Proposed Method 2	$\Phi = \frac{\gamma H_s^2 C_g}{2\gamma QS}$	$\Phi = \frac{H_s^2 C_g}{2QS}$

Table 3.4. Sensitivity of Proposed Method 3 to different allowable ranges of accuracy

Maximum number of days before or after a closure event within which a model prediction is "correct"	**Maximum possible percentage of closures predicted (no limit to no. of incorrect predictions)**	**Percentage of closures predicted allowing no more than 10 incorrect predictions**
1	74.2%	62.1%
2	80.3%	69.7%
3	81.8%	72.7%
4	83.3%	77.3%
5	84.8%	80.3%

The only parameter that was adjusted in this case was the range in which predictions were considered "correct". An infinitely large range would produce the maximum number of correct predictions, whereas an infinitely small range would produce none.

Sensitivity analyses were conducted for changes in the wave group velocity and inlet channel slope to ensure the correctness of the simplifying assumptions made regarding these parameters. Table 3.5 shows that increasing the slope slightly decreases the accuracy of the Proposed Method 3, while Table 3.6 shows that changing the group velocity has no effect. Separate analyses of the wave and tide data used to produce model predictions were also performed. Table 3.7 shows that the use of nearshore wave data provided the best model results. This underscores the importance of having estimates or measurements of waves in the vicinity of the inlet for a study of inlet stability and closure, especially when the beach topography and offshore bathymetry alter the incoming wave climate, such as at the estuary of the Russian River.

Table 3.8 shows the surprising result that using ocean tide measurements rather than in-estuary tide measurements provided better model results in this case. While both types of data provide the same maximum number of correct predictions, using in-estuary measurements of tidal fluctuations produced lower accuracy than for offshore tide measurements when the model was limited to produce no more than 10 errors. A possible explanation for this is that values of the in-estuary tide range will be smaller than in reality if they are calculated as the difference between HH and LW. In tidal inlet systems with no river inflow, tidal flows are the primary cause for variations in water level. In an estuary with moderate river flow, the minimum elevation of the water in the estuary is controlled by the river water flowing through the mouth, which allows the water level in the estuary to stay above the minimum inlet channel elevation. When the river delivers large amounts of water to the ocean, large amounts of freshwater can raise the depth of flow through the inlet, and the LW elevation will be different from what it would have been from tidal influence alone. For this reason, the tide range calculated from the HH and LW levels in the estuary will at times produce unrealistically small tide ranges. This would cause the models to produce slightly higher stability index values and predict closure events in error.

Table 3.5. Sensitivity of Proposed Method 3 to changes in slope

Slope (m/m)	Percentage of closures predicted	No. of erroneous predictions
.01	71.2%	15
.005	71.2%	14
.001	80.3%	10
.0005	81.8%	5
.0001	83.3%	2

For each change in slope, the stability threshold was adjusted to find the maximum percentage of closures predicted.

Table 3.6. Sensitivity of Proposed Method 3 to changes in wave group velocity

Assumed depth at river mouth (m)	Resulting group velocity (m/s)	Percentage of closures predicted	No. of erroneous predictions
1	3.13	80.3%	10
2	4.43	80.3%	10
3	5.42	80.3%	10
4	6.26	80.3%	10
5	7.00	80.3%	10

For each change in group velocity, the stability threshold was adjusted to find the maximum percentage of closures predicted

Table 3.7. Sensitivity of Proposed Method 3 results to wave data type

Type of wave data used	Percentage of closures predicted	No. of erroneous predictions
Deep-water wave measurements	83.3%	44
	65.2%	10
Near-shore wave estimates	84.8%	29
	80.3%	10

For each wave measurement type, the stability threshold was first adjusted to find the maximum number of correct predictions, and second, it was adjusted to limit the number of errors to 10.

Table 3.8. Sensitivity of Proposed Method 3 to tidal data type

Type of tide measurements used	Percentage of closures predicted	No. of erroneous predictions
Offshore measurements	86.4%	29
	80.3%	10
Estuary measurements	84.8%	29
	66.7%	10

For each tide measurement type, the stability threshold was first adjusted to find the maximum number of correct predictions, and second, it was adjusted to limit the number of errors to 10.

3.7. Conclusions

The results of the study demonstrate that a simple parametric model can predict closures of an unstable inlet with a good degree of accuracy. Ultimately, several of the methods introduced herein showed a modest capacity to recreate the record of closure, which is impressive considering the complexity of the system and the number of secondary processes that were neglected, such as seepage, evaporation, and channel morphology. The most accurate method was Proposed Method 3, which takes into account wave, tide and river influences. These simple models only provide a rudimentary method for predicting closure events based on measured tide, wave, and discharge characteristics, and cannot explain complex morphological changes or differentiate between the mechanisms of sediment transport that ultimately lead to inlet instability.

This study suggests that tide and river flow act conjunctively to prevent closure, and therefore the influence of tides cannot be neglected when the strength of river influence is seasonal. While both of these contributors can prevent closure, a weak river or neap tide will not lead to closure unless the wave climate reaches a sufficient intensity. The methods studied here should only be used as an initial estimate of stability, and will not provide more accurate results than a fully developed computational model. Future study of these methods at additional sites is recommended. These conclusions are applicable to the Russian River and similar inlets where tides, waves, and discharge are all important.

Table 3.9. Symbology

Symbol	Definition	Assumed value (if applicable)
Φ	Stability index	
h_r	tide range	
γ	Specific weight	1030 kg/m^3 for seawater
S	Slope	0.001 m/m along inlet channel
P	Tidal prism	
T	Tidal period	6.25 hours from HH to LW
C_g	Group velocity	
L_0	Deep-water wave length	
H_0	Deep-water wave height	
T_w	Wave period	
F	Dimensionless coefficient[1]	1
b	Inlet width	
Q	discharge	

[1]See O'Brien (1971)

Chapter 4. Morphology Of An Unstable Rivermouth: The Case Of The Russian River, California

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Keywords: morphology, tidal inlet, estuary

Abstract

Inlets which experience sedimentation and closure despite having river influence exist in various regions of the world. They are complex systems whose behaviors are mostly controlled by variations in river flow, tidal influence and wave energy. When any of these natural controlling mechanisms change in magnitude, the inlet system invariably responds to the change by making morphological adjustments that can be witnessed at daily, seasonal, and annual time scales. Observations of these adjustments are rare, and the behavior of unstable inlets that coincide with seasonal river mouths is not fully understood. The morphological behavior of the Russian River was studied for the period from 1990 to 2006. A unique photographic dataset was donated by a resident of Jenner, California, near the mouth of the river. This record was analyzed and compared to available data from nearby wave, tide, and discharge measuring stations. A set of classifications for types of inlet configurations was introduced in order to compare the shape of the inlet with other parameters. The results indicate that the influence of each of the processes that affect inlet stability and morphology vary by the time scale of consideration. A threshold suggested by Komar (1996) was investigated by modeling the width of the inlet, and by making observations of the changes in inlet width and length

during different seasons. The width was modeled by fitting width data to tide range or river discharge data and using the threshold to determine when each fit was appropriate. This threshold indicates whether the river or the tides have more control over the morphology of the inlet at any given time.

4.1. Introduction

The closure habits and morphology of inlets have been the focus of study for more than a century. Inlet systems provide entryways to sheltered harbors and also house unique and diverse ecosystems. They are important to maritime industries, plant and animal wildlife, and a multitude of people who rely on the adjacent lagoon or estuary for fishing and floodplain agriculture. Research efforts over the years have provided relationships that help describe the behavior of these systems, and have given rise to the stabilization of many inlets for commercial purposes. However, many of the relationships used as management tools and as descriptors of inlet behavior are either empirical or neglect many relevant processes, and cannot represent the characteristics of all of these systems indiscriminately (Jarrett, 1976; Byrne and Gammisch, 1980). In addition to wave and tidal processes, there are many other external controls on tidal inlets including sediment supply, basinal geometry, sedimentation history, regional stratigraphy, riverine discharge, and sea level changes (FitzGerald 1996). Even the mouths of seasonally strong rivers have been known to close in many regions such as California, South Africa, Brazil, and India. The majority of research has focused on tidal inlet systems with naturally large, navigable channels, and negligible river influence. As a result, many aspects of unstable inlets remain unclear. For example, the morphological behaviors of small estuarine inlets, which are found in most regions of the world, are widely unobserved. A wide spectrum of inlets lose their communication with ocean waters through sedimentation and closure either seasonally or sporadically, and exhibit various types of morphological change. Some of these systems have become unstable over time as a result of land-use, but many have demonstrated unstable behavior such as migration and closure for as long as humans have witnessed them. A full understanding of tidal inlets will require the careful observation of these systems as they behave naturally in their environments.

As noted by Hughes (2002), stable inlets, where the minimum cross-sectional area remains relatively constant with time, imply a dynamic balance between the currents in the inlet and deposition of littoral sediments. Sediment moving along the coast is deposited into the inlet, and the tidal and riverine flow moves the sediment out of the inlet channel. Unstable inlets are associated with a tendency to fill with sediment and in some cases close completely. Ephemeral or unstable inlet systems lack sufficient river flow or tidal influence to prevent sedimentation in the inlet. These inlets usually occur in wave-dominated coastal environments where strong seasonal variations of river flow and wave climate coincide with moderate or low tide ranges (Ranasinghe and Pattiaratchi, 2003). Although some inlets coincide with the mouths of rivers, inlet dimensions and sediment transport trends in these cases are still governed to a large extent by the tidal processes (FitzGerald, 1996). However, when the tidal range and incident wave power of the receiving basin are negligible or small relative to the strength of river outflow, river-dominated configurations result (Wright and Coleman, 1972, 1973).

The aim of this study is to capitalize on the availability of field evidence for the Russian River to answer questions about the behavior of naturally unstable inlet systems with seasonal river influence. The Objectives of this study are as follows:

(1) Gain an understanding of the relationship between external forcing from tides, waves, and river discharge and the morphological response observed at the Russian River inlet.

(2) Investigate the behavior of this system at annual, seasonal, and daily time scales.

(3) Find evidence that a threshold exists which dictates whether the river or tides control the morphology of the inlet.

In Section 2, we present a review of the morphological response of inlets. This will be followed by a section on the geometry and migration of inlets as well as a description of the study site. Section 5 will describe the methods used to obtain the dataset that was used in the analysis. Subsequently, the results of the data analysis will be presented, followed by a summary of the conclusions.

4.2. Morphological response of inlets

Fundamental differences in inlet morphological response to local conditions have increased the caution of researchers who use the empirical relations presented within the last century. Research by Mayor-Mora (1977) and Byrne and Gammisch (1980) has shown that inlets with cross-sectional areas smaller than 100m^2 cannot be understood from the commonly used empirical relationships of O'Brien (1969) and Jarrett (1976) relating tidal prism to inlet cross-sectional area. O'Brien has suggested that small inlets are not dynamical models of large inlets when subjected to the same tidal variations and littoral transports. Tidal inlets may also owe much of their differences to factors other than cross-sectional area and tidal prism, such as the local wave climate. A commonly discussed result of Jarrett's work is the finding that Atlantic coast inlets have larger cross-sections for a given tidal prism than do their counterparts on the Pacific coast. Several authors have pointed towards the difference in wave climates between these coasts to explain this phenomenon (e.g. Jarrett, 1976).

Despite these differences, there are several common aspects shared by most inlets. An aspect which has received much attention is the tendency for inlets to reach a dynamic equilibrium between scouring from inlet currents and sedimentation from wave-induced transport. The shift towards this equilibrium can take as little as days or as long as centuries. In the first half of the twentieth century, the Netherlands diked a substantial portion of the Frisian Sea, greatly decreasing the tidal prism of the basin. Using an extensive record of depth measurements, Kragtwijk et al. (2004) showed that it will take centuries for the entire Frisian Sea inlet system to fully adapt to the effects of the closure and to regain a new dynamic equilibrium state. Evidence has also shown that inlet systems undergo cyclical trends that are unrelated to land-use changes. Cayocca (2001) suggested that an apparent cyclical nature of the configuration of inlet channels is a long-term feature; however, it cannot be reproduced without taking into account short-term events (such as the opening of a breach during a storm). The effect of short term changes in the external forcing of inlet systems, such as storm-surges or floods, can have a profound impact on inlet morphology. Ultimately, the morphological behavior of an inlet will depend on site characteristics and the complex interaction of many processes, as well as cyclical trends and responses to change that can be viewed at different time scales.

4.3. Geometry and Migration of Inlets

Inlets residing in alluvial shores often demonstrate common responses to changes in external forcing from waves and currents. As argued by O'Brien (1971), the shape of the inlet is influenced by the wave induced sand transport alongshore towards the inlet, and by the scouring action of tidal currents. Both large and small inlets respond to changes in the scouring ability of inlet currents or the supply and transport of sediment by adjusting their channel geometry. Inlet geometry is important because it governs the degree of damping of the tidal fluctuations in the adjacent lagoon or estuary (Moody, 1988). In systems where the tidal prism is the only source of inlet currents, a change in geometry and a corresponding damping of the tidal fluctuation can ultimately lead to inlet closure. Systems with river influence are not exempt from this result if flows are only seasonally strong, and a change in tidal prism often produces a comparable level of instability.

Inlets also respond to instability by migrating, a behavior that is generally more common for small inlets. As an inlet migrates, the channel connecting the inlet mouth to the bay can elongate, which increases frictional factors, attenuates tidal flow, and can also decrease the tidal prism (FitzGerald, 1996). Dean and Dalrymple (2002) provide an explanation for inlet migration based on the observation that inlets tend to migrate in the direction of the longshore sediment transport. Commonly, sediment deposits on the up-drift shoulder of the entrance channel, which leads to a momentary decrease in the channel cross-sectional area and a corresponding increase in the inlet current velocity. If the down-drift bank has limited sediment supply, it will erode without an accompanying deposition, whereas the material eroded on the up-drift bank will be replaced by additional deposition associated with the longshore sediment transport. While migration is commonly associated with longshore transport (i.e. transport parallel to the coast), on-shore or cross-shore transport has been found as the dominant source of inlet instability in many systems, and can give rise to similar morphological responses.

Large tidal prisms and consistently large river flows prevent instability in inlet systems by providing sufficient inlet currents to prevent sedimentation from ever taking place. It is sometimes unclear whether the tides or river flow control the behavior of the inlet in a system with a seasonally strong river. Systems with a strong river do not need the help of tidal fluctuations to maintain a stable inlet. However, many inlet systems with negligible freshwater inflows have large tidal prisms which are sufficient on their own to prevent closure from ever occurring. When both influences are present, the morphology observed in inlets is likely controlled by a combination of these processes (in addition to many other external processes), but a change in the magnitude of either will likely increase the role of one over the other. A threshold may exist which would separate estuaries controlled by river influence from those controlled by tides. Komar (1996) proposed the idea that this threshold is the ratio of the volume of river inflow to the tidal prism during a tidal cycle.

4.4. Study site

The site of the current study is the Russian River Estuary, in northern California. This system experiences sporadic inlet closures which follow a general seasonal pattern. This estuary is remarkable because it has not experienced credible sedimentation within the last century despite a history of land-use changes, and because its history suggests that it is inherently unstable despite its partially sheltered location (see figure 4.1) and significant river flows. Historical records indicate that this tidal prism is approximately the same or less than conditions in 1876. This is important to note because many estuaries in California have become unstable over the last century as sedimentation has decreased the sizes of their tidal prisms. Despite the lack of change at the Russian River Estuary, historical records also indicate that this tidal prism is insufficient to prevent closure. The earliest historic accounts of the estuary by the Russian settlers describe the need to drag boats across the barrier beach formed at the mouth in order to gain access to the estuary, which implies that the estuary was subject to periodic closure before major land-use changes occurred in the watershed (Goodwin and Cuffe, 1993).

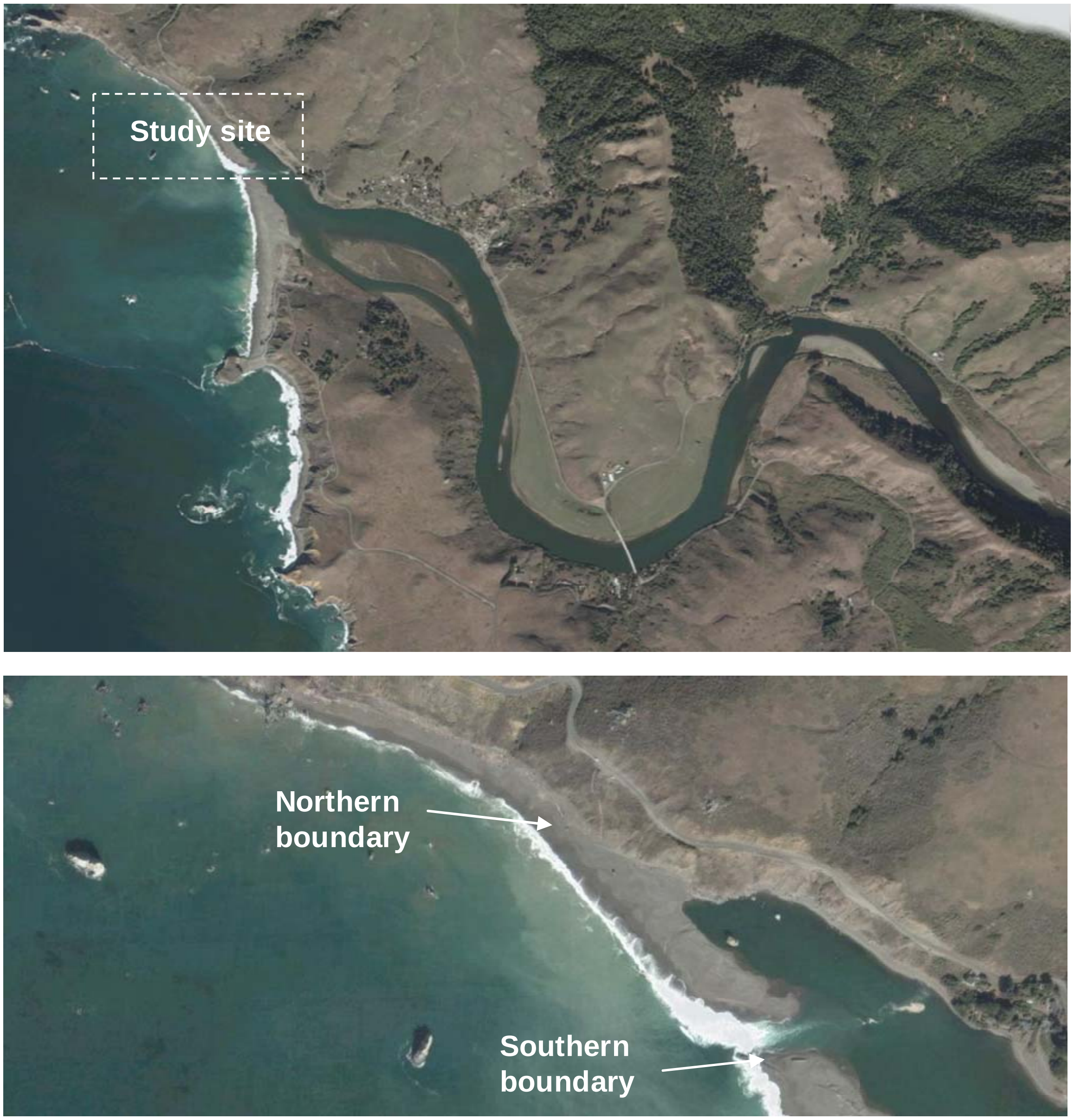

Figure 4.1. Location of Russian River inlet and boundaries of inlet movement. Photograph is available from GoogleEarth.

The mouth of the river forms an ecologically important estuarine system, and like many other estuaries in California, it is “mesotidal” according to the classification of Hayes (1979), with a maximum tide range slightly above 2 meters. Also in common with many other California estuaries, the local wave climate is very energetic. In general, the estuarine portion of the Russian River extends approximately 6 to 7 miles upstream, from the mouth of the river between Duncans Mills and Austin Creek (Rice, 1974). This location is visible on Figure 2.3. An approximate estimate of the maximum tidal prism is 1750 acre-feet and for the mean tidal prism is 1300 acre-feet in 1992 (Goodwin and Cuffe, 1993). The Russian River drains an area of 1485 square miles in Mendocino and Sonoma Counties in Northern California. The River is approximately 110 miles long and is the largest river on the California coast between Point Delgado and San Francisco Bay (U.S. Army Corps of Engineers, 1965). The majority of the annual precipitation occurs between October and May, usually in a few events of relatively short duration. Two major upstream reservoirs regulate the flow in the river and provide minimum flows for fish during the summers. This release of flows during the summer has significantly reduced the variability of the river discharge during this season. During winter flow conditions and significant storm events the flood peaks are reduced due to the operation of the reservoirs for flood control purposes (Goodwin and Cuffe, 1993). A jetty completed in 1941 forms the southern boundary of inlet movement along the barrier beach, and constrains the range of movement of the mouth to a distance of 400 meters. The jetty was constructed in order to stabilize the mouth of the river, but failed in its purpose, and no other construction has taken place at the barrier beach since its completion.

High-energy waves characterize the winter season while a corresponding low-energy wave climate predominates during much of spring and summer. The waves that occur in the vicinity of the river mouth consist of both “sea” and “swell” and the predominant wave in the study area is from the northwest with an average period from 12 to 16 seconds (Rice, 1974). The storms which generate the swell waves that reach the Russian River inlet are seasonal, and take place in various parts of either the northern or southern hemisphere in the Pacific Ocean depending on the time of year (Goodwin and Cuffe, 1993). As the intensity of these storms varies in location, so does the direction of the incoming swell waves, and correspondingly, the direction of longshore sediment transport. Figure 4.1 shows that the beach is partially sheltered and has several offshore rock outcroppings. It is unclear how exactly the wave climate changes between the offshore measuring station and the inlet. A model that includes wave refraction and diffraction might produce accurate results for nearshore wave heights and direction, considering the possible effects of the rocks offshore, and it is believed that wave measurements near the mouth of the river will provide the only accurate estimation of wave parameters for future study.

The Russian River inlet displays characteristics of a system which is rarely stable. When the storm-related high discharge events of the winter and spring are not present, the river migrates almost continuously and closes frequently. While closures never last more than two weeks, they occur as many as 15 times a year. Figure 4.2 illustrates a closure event taking place during November of 2003. The river is generally believed to be stable during months associated with high precipitation, but this is not always the case, as closure events over the last 20 years have taken place in every month of the year. Closures during winter months typically take place during dry years when flows are lower than average. The estuary water level above the NGVD 1929 datum is monitored by the Sonoma County Water Agency, which breaches the barrier beach to create a new inlet whenever the water level rises above a certain elevation. This type of management has taken place for many decades, for the purpose of preventing flooding of nearby houses and floodplain agriculture. Even if the mouth was not artificially breached, enough water would accumulate behind the barrier beach from river flow to overtop the barrier within several weeks, even during the summer months. The river prevents closure from lasting for the duration of the summer and fall at this estuary, however, closures spanning several months are not uncommon among this type of system, especially in arid locations such as Australia (e.g., Ranasinghe and Pattiaratchi, 2003). Most importantly, the river exhibits morphological response to conditions which can be noticed at daily, seasonal, and annual time scales. In addition to the largely unchanged bathymetry of the estuary over time, this provides a rare chance to understand how a naturally unstable estuarine inlet system responds to external forces.

November 17, 2003

November 22, 2003

November 20, 2003

November 24, 2003

November 21, 2003

November 29, 2003

Figure 4.2. Inlet movement during November, 2003. Courtesy of Elinor Twohy.

4.5. Methods

Data was made available for the present study from a resident of Jenner, California who observed the river on a daily basis for 28 years from 1979 to 2006. Observations included events of opening and closure of the inlet, air temperature and "stormyness", among others. Additionally, the observer took daily photographs of the inlet from 1990 to 2006. The photographs were taken from two separate sites, each within 1000m of the inlet. The majority of the pictures were taken from a site on a highway turnout above the mouth of the river, which gave an excellent view of the inlet and the barrier beach.

Satellite imagery made available by GoogleEarth was used along with the provided photographic record to make estimates of certain geometrical and locational characteristics of the inlet. An embedded tool for measuring distances on satellite images was used to measure the distance between several landmarks on the beach within the limits of inlet movement. Some of the landmarks, including the jetty which forms the southern boundary of inlet migration, were measured on-site to verify the values used from the satellite imagery. Nearly all photographs included in the dataset show the inlet and several large boulders on the beach which are also visible in satellite images. The width and length of the inlet were estimated based on their respective size relative to the known distances between these monuments. Additionally, the location of the inlet on the beach and the shape of the inlet were estimated from the photographs. Although the record of inlet width, length, and location spans the same period for which the photographs were available, there are several gaps during the years 1991-1994 since some of the available pictures during this period did not clearly show the inlet. Errors in estimates of these values are expected to be within 10 meters of actual values for width and location estimates and within 20 meters for length estimates. Inlet migration was also measured at the study site. The record of daily inlet position on the beach was quantified by referencing the location of the inlet as a distance north of the southern boundary of migration. The absolute distance that the mouth moved each day was measured using the data and the total movement was calculated as a sum of these daily movements for each year.

Straight

Minimal curvature in the channel

Arcuate

Channel takes the shape of a single arc

Meandering

Channel includes two or more arcs

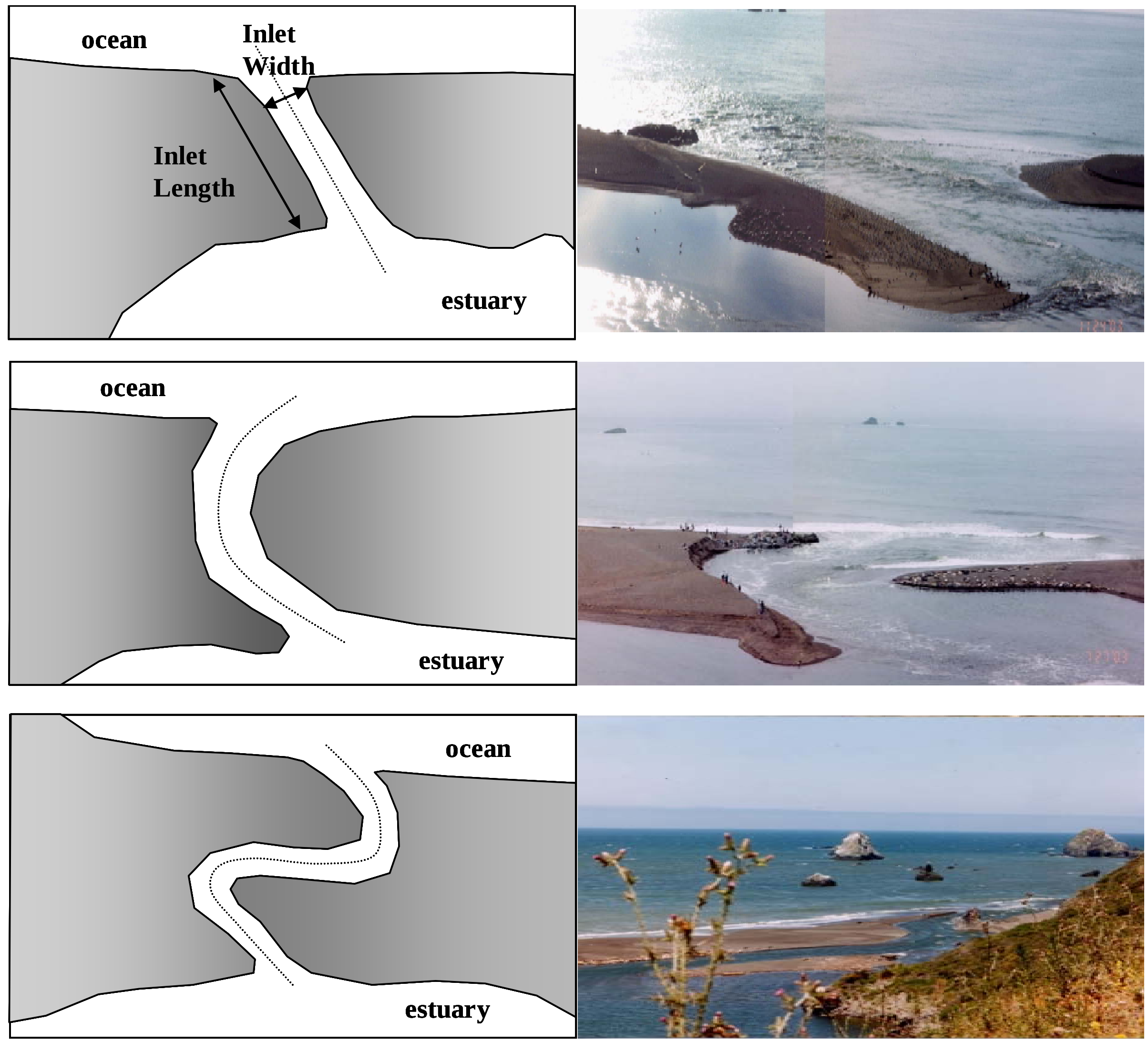

Figure 4.3. Classification of inlet configurations. Photographs courtesy of Elinor Twohy.

The shape of the inlet was analyzed by introducing a classification that delineates inlet shapes by their degree of curvature. This classification is explained by Figure 4.3. It was introduced in this study to identify the characteristics of inlet shapes with different hydraulic efficiencies. It allows for a comparison of the shape of the inlet with river flow, tide magnitude, wave climate, and risk of imminent closure. The "straight" configuration is assumed to be the most hydraulically efficient, whereas the "meandering" configuration is assumed to be the least efficient.

Measurements of river discharge, offshore wave heights, and tidal variations were used in this study to find correlations between these parameters and the morphological behavior of the inlet. Wave measurements were acquired from the Coastal Data Information Program (CDIP) Cordell Bank buoy, stationed 39 miles south of the Russian River mouth. To create estimates of nearshore wave heights based on this data, a transformation matrix provided by CDIP was used to take into account the effects of wave refraction between the measurement station and the shoreline of interest. This method is based on wave theory, and did not account for wave diffraction or reflection. It was used to account for the effects of the local bathymetry and coastline topography in altering the wave climate in its travel from the measuring point offshore to the inlet. Tide measurements were obtained from the National Data Buoy Center (NDBC) Bodega Buoy 19 miles south of the river mouth. Additionally, the Sonoma County Water Agency provided hourly water level measurements above the NGVD 1929 datum within the estuary. River discharge measurements were available from the archives of the California Data Exchange Center for the Hacienda Bridge station, 11 miles upstream of the inlet.

Between this measuring station and the inlet, the only other sources of freshwater inflow are several small creeks, of which Austin Creek is the largest. Records from the United States Geological Survey showed that the freshwater contributions of this creek to the Russian River Estuary were only relevant during winter months when precipitation is high. During this time, the flows in Austin Creek amount to only a small fraction (no more than 10%) of the flows contributed by the Russian River itself, and were thus neglected along with the other ephemeral streams in the vicinity of the estuary.

Inlet width was modeled for the period spanning from June 17, 1999 to December 19, 2006 to find evidence of a threshold that indicates when the river or the tides have more influence over the morphology of the inlet. This period was chosen because it coincides with the range of estuary water level data provided by the Sonoma County Water Agency. It was assumed that tidal fluctuations within the estuary would have a stronger correlation with inlet width than offshore measurements, because the inlet configuration or elevation can alter the range of tides that enter the estuary, as shown by PWA (2004). The following steps were taken to verify the existence of the threshold:

1. A threshold discharge (Q_t =15 m^3/s) was set, based on observations of inlet behavior.
2. Inlet width was plotted against estuary tide range for days when $Q < Q_t$ and a linear fit was created to represent the relationship between width and tide range (see Figure 4.4a).

3. Inlet width was plotted against river discharge for days when $Q > Q_t$ and a power fit was used to represent the relationship between these parameters. (See Figure 4.4b).
4. The width of the inlet was predicted for a test period lasting from January to September of 2003 using the fits based on tides and discharge, respectively.
5. Inlet width was predicted using the threshold to delineate which parameter would most likely control the size of the inlet. Whenever $Q > Q_t$, the power fit based on discharge predicted the inlet width. When $Q < Q_t$, the linear fit based on estuary tide range was used.

A linear fit was chosen to create a relationship between tidal fluctuations in the estuary and inlet width, because it produced better results than any other type of fit. This was true of the power fit used to represent the relationship between river discharge and inlet width.

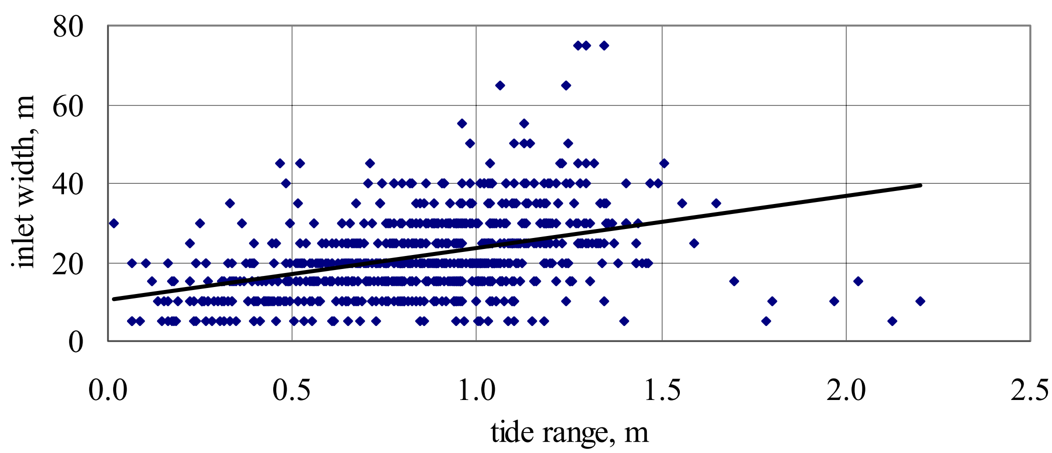

Figure 4.4a. Inlet width vs in-estuary tide range (for river discharge Q lower than Q_t = 15m^3/s) for the years 1999-2006.

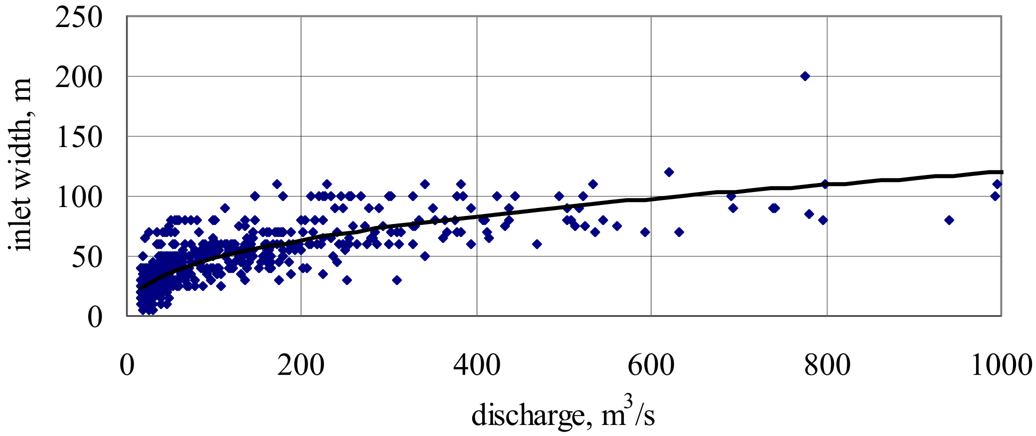

Figure 4.4b. Inlet width vs discharge (for river discharge Q greater than Q_t = 15 m^3/s) for the years 1999-2006

4.6. Results

4.6.1. Results of inlet shape analysis

Table 4.1 summarizes the results of the inlet shape analysis. No specific ranges of discharge, tide, and wave heights could be set for any of the configurations because each configuration existed for a variety of conditions. However, Table 4.1 shows that the average conditions varied considerably. Wave and tide values appeared to be irrelevant here (not shown), but susceptibility of closure, discharge, and inlet geometry have very different average values depending on configuration. Particularly noteworthy is the fact that once the inlet begins to meander, it has a very high likelihood of closing within two weeks. These results identify which inlet shapes can be associated with inlets that are staying in an equilibrium state and which inlets are filling with sediment and closing. In general, both the straight and arcuate configurations of the inlet channel can be associated with inlets that are likely to remain open for some time, although arcuate inlets have a slightly higher chance of closure. When the inlet is meandering, closure is likely to occur within two weeks, which indicates that this configuration may be very inefficient hydraulically, leading to lower inlet current velocities and increased sedimentation from waves.

Table 4.1. Characteristics corresponding to different inlet configurations

Inlet Configuration	Avg discharge (m^3/s)	Avg width (m)	Avg length (m)	Probability of closure occurring within 2 weeks
Straight	100	40	75	0.3
Arcuate	25	25	143	0.35
Meandering	17	15	200	0.76

See Figure 4.2 for a visual definition of each configuration type

4.6.2. Behavior at the yearly time scale

Analysis of the data showed several long-term trends in behavior that characterized the period lasting from 1991 to 2006. Table 4.2 shows that the amount of time that the river was closed each year varied considerably. This closure duration varied from a high of 109 days in 1991 to a low of 10 days in 2006. These durations are sums of several closure periods and do not imply that closure lasted for the entire number of days listed, consecutively. It is not clear how the discharge of the river would change during the summer if upstream dams were not in place, and it may be the case that the river was less stable when it wasn't subjected to consistent, low dam release flows during the summer. Yearly average discharge was plotted along with the annual duration of closures in Figure 4.5 to show the inverse relation between these two parameters. This may imply that the strength of the river is the most important factor in maintaining a stable inlet in a time scale of years. Both Rice (1974) and Goodwin and Cuffe (1993) argued that the tidal prism of the Russian River Estuary is insufficient to keep the inlet open on its own, so the result that drought years produce greater durations of closure than flood years is understandable. Inlet width and length were not analyzed at this timescale, because several years had periods where the photographic record was incomplete, or did not show the inlet clearly enough to allow for estimates of these parameters to be made.

Table 4.2. Closures during the study period

Year	**Number of closures**	**Number of days closed**
1991	13	109
1992	9	67
1993	7	51
1994	13	81
1995	5	21
1996	8	54
1997	14	82
1998	11	38
1999	14	51
2000	15	63
2001	10	62
2002	9	35
2003	3	16
2004	7	55
2005	6	28
2006	4	10

The total migration of the inlet in each year was also calculated, and a summary of the results is shown in Figure 4.6. Although the net migration of the inlet either north or south along the beach cannot total more than 400 meters, the total, or gross movement, was typically much greater than this distance. In fact, in all but the years 1995, 2004, and 2006, the river mouth moved more than one kilometer within its bounds. No correlation was found between total yearly migration and any other measured parameter. The data suggests that there was a peak in migration during the years 1998 and 2000. Before and after these years, migration was much lower, and the current trend shows that the amount of migration has decreased steadily towards the year 2006, when it was the lowest of period of record.

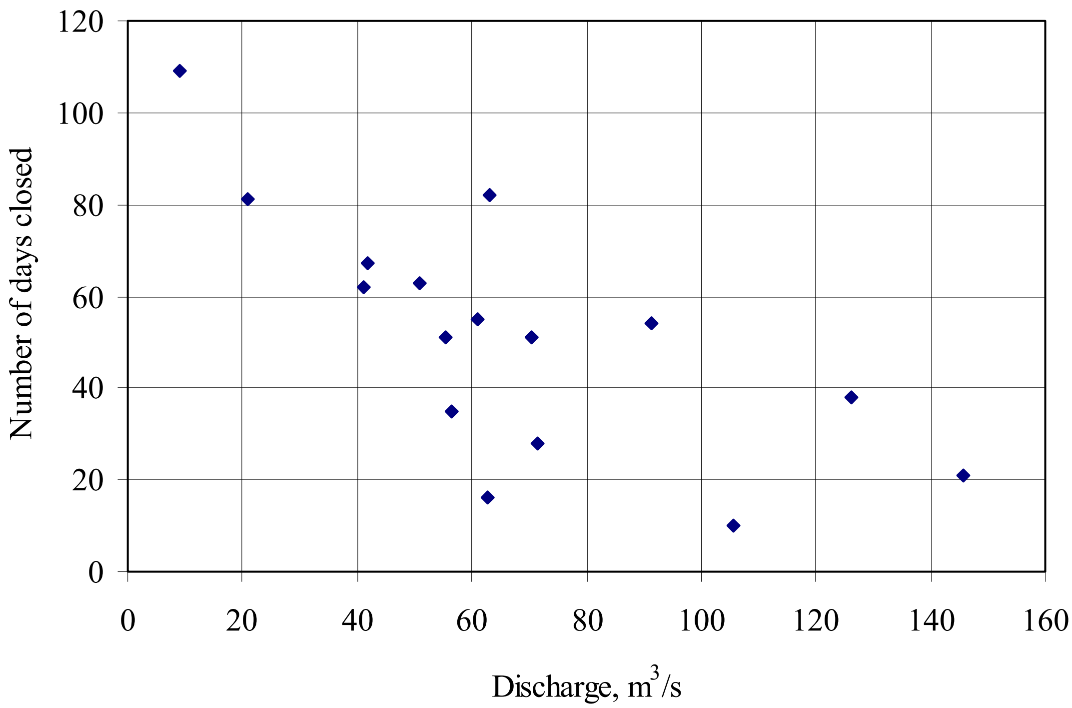

Figure 4.5. Comparison of river discharge and closure duration for the period of 1991-2006. In this case, discharge is averaged over the course of a calendar year.

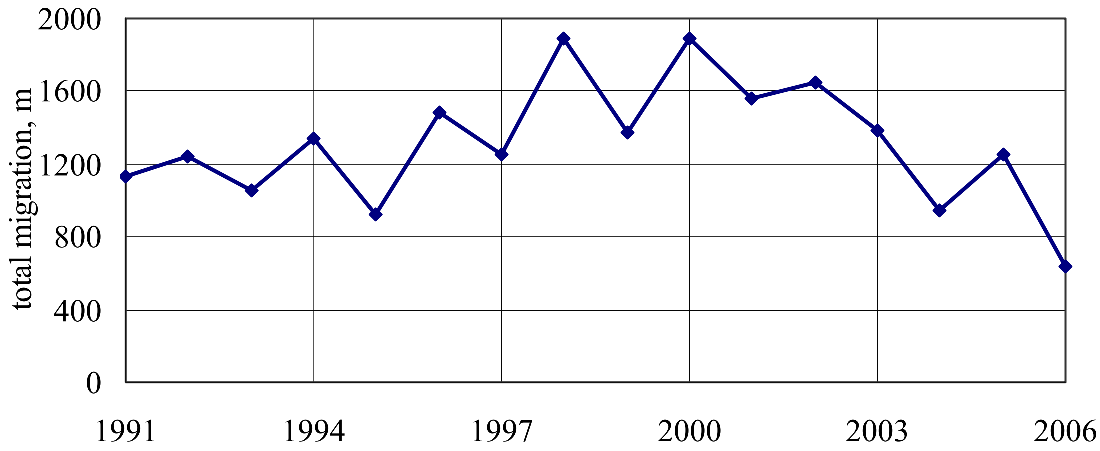

Figure 4.6. Total yearly migration of the Russian River inlet for the period of 1991-2006.

4.6.3. Behavior at the seasonal timescale

At the seasonal timescale, inlet migration follows a repeating seasonal pattern and the available data implies that this pattern may have shifted in the 1990s. In late fall or early winter, the inlet migrates from a location near the jetty to a location near the north end of the beach. As the direction of incoming waves switches during the spring or summer, the inlet migrates back towards the jetty, but the rate and continued direction of the migration varies depending on the continued intensity and source direction of the waves. Figure 4.7. shows that for the years 1991 to 1994 the inlet migrated slowly back towards the southern boundary of migration during the summer, and sometimes did not fully return until after October. Figure 4.8a shows the movement of the river mouth in the water year spanning 1991 and 1992. Starting in 1995, this migration pattern changed. For all of the years from 1995 to 2006 except for 1998, the inlet migrated southward from the northern boundary much more rapidly. In addition, the migration became less steady, and the inlet often switched directions for several weeks at a time. Figures 4.8b and 4.8c illustrate this. Figure 4.8d shows that in 2005, the inlet never migrated more than 100 meters towards the northern boundary before returning to the jetty. It is not certain whether this behavior will continue, or switch back to the pattern observed before 1994, but it is probable that this change in behavior is caused by a change in the wave climate reaching the mouth of the river.

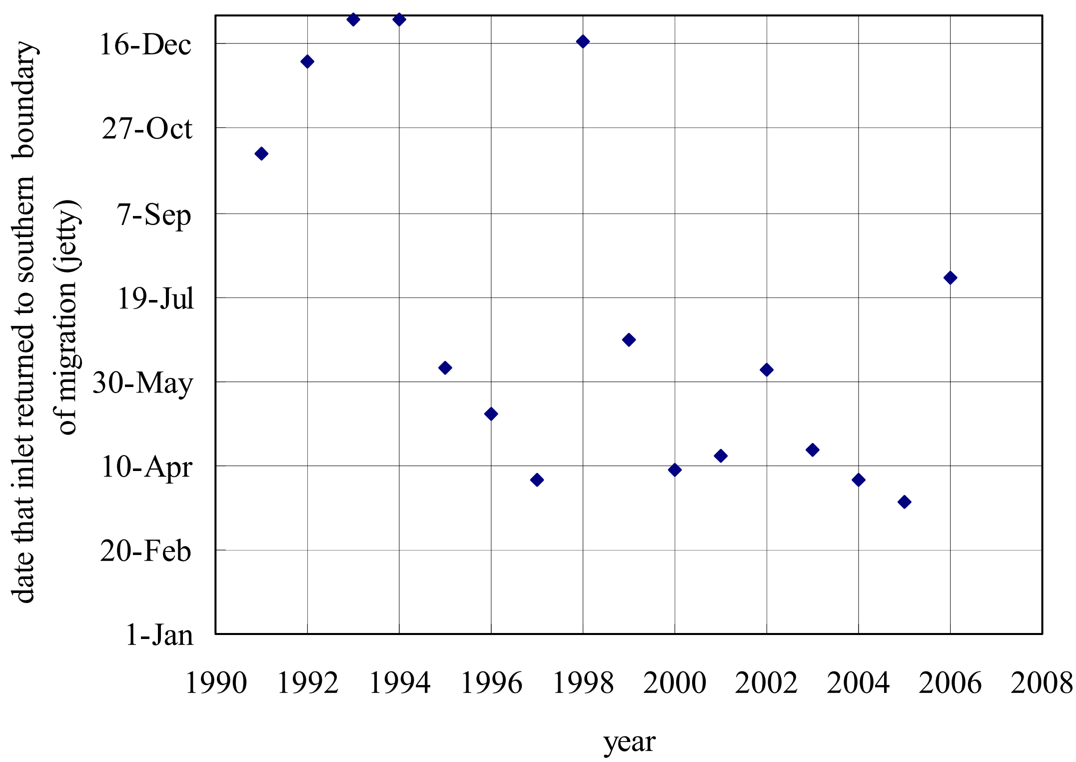

Figure 4.7. Date that the inlet returned to the southern boundary of migration after migrating northwards during the winter. During the years 1993 and 1994, the inlet did not return to the southern boundary before the calendar year ended. They are represented as points at December 31.

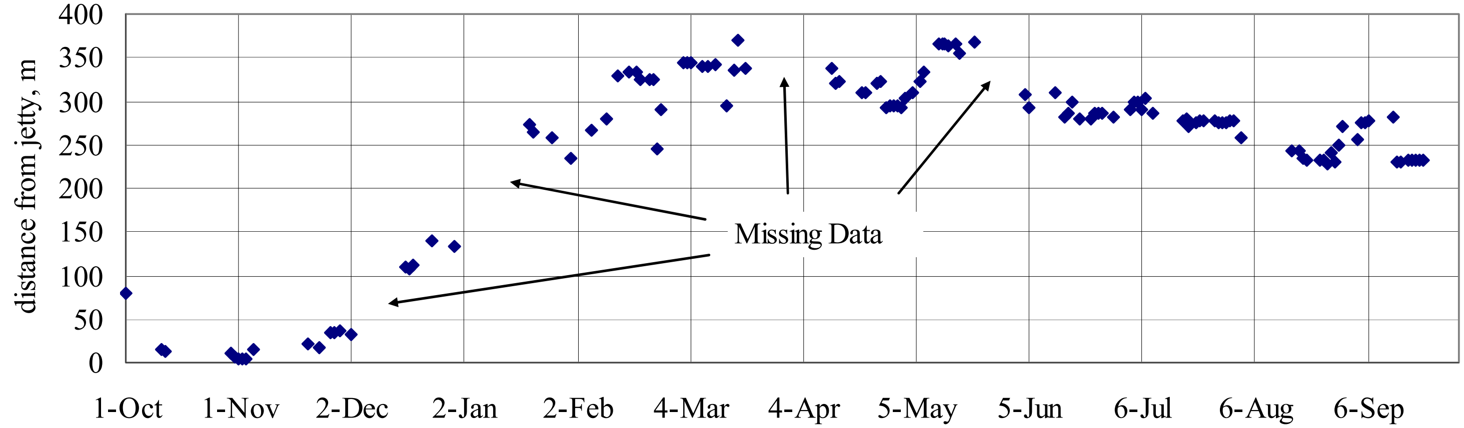

Figure 4.8a. Russian River inlet movement in terms of distance north of the jetty for water year 1991-1992

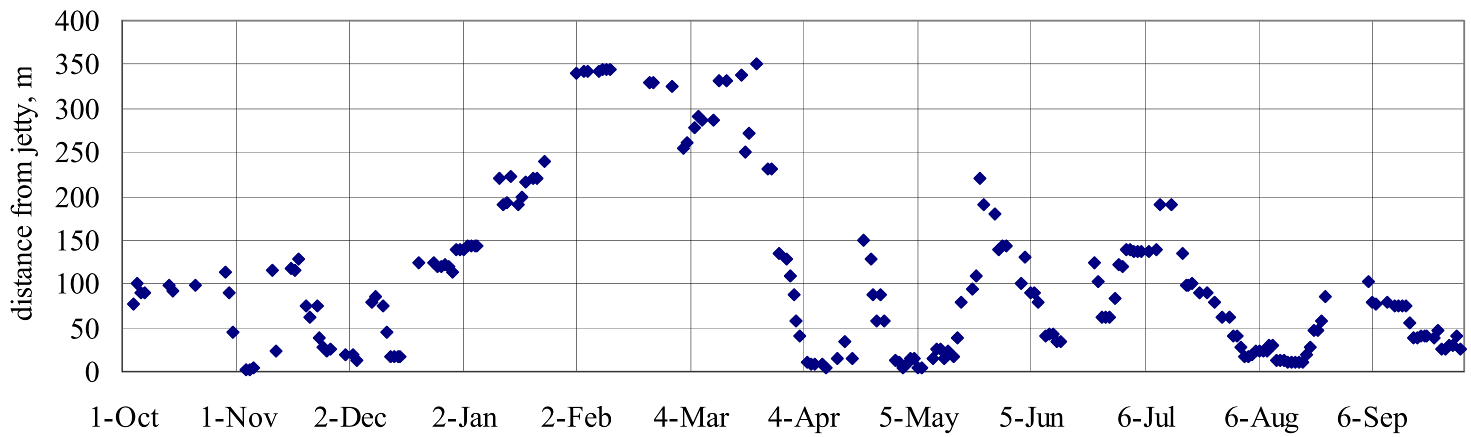

Figure 4.8b. Russian River inlet movement in terms of distance north of the jetty for water year 1999-2000

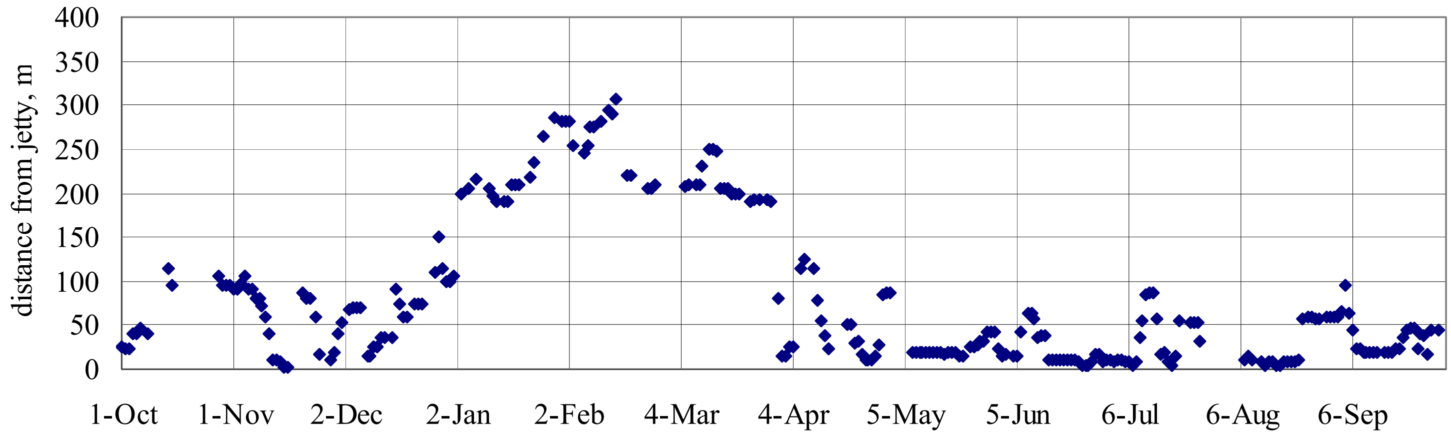

Figure 4.8c. Russian River inlet movement in terms of distance north of the jetty during water year 2003-2004

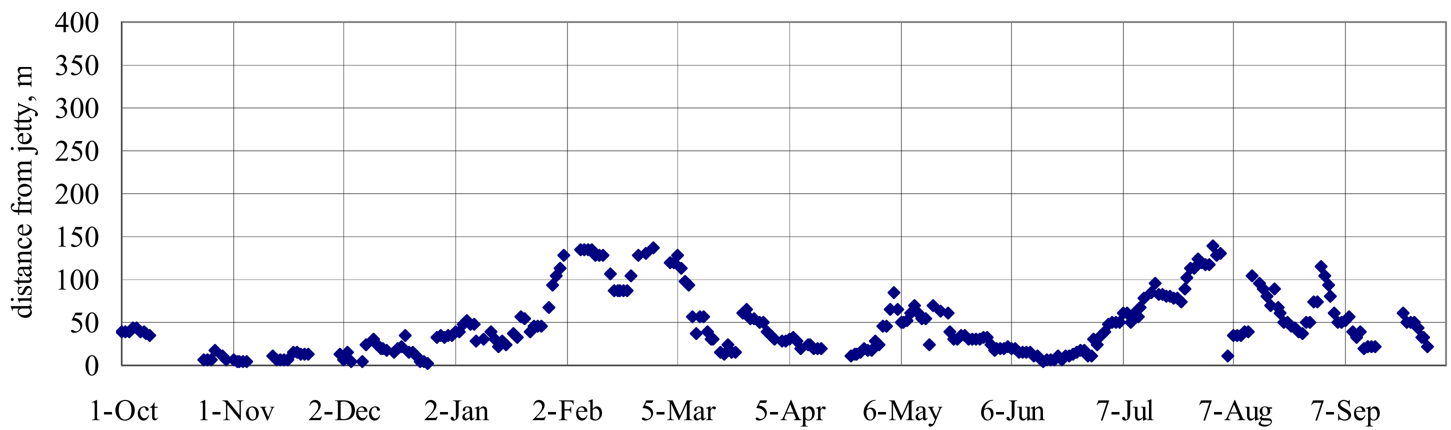

Figure 4.8d. Russian River inlet movement in terms of distance north of the jetty during the water year 2004-2005

The closure habits of the Russian River are easily explained using an analysis at the seasonal time scale. Figure 4.9 shows that the majority of closures at the Russian River take place during the months of October and November. This phenomenon is explained by Figure 4.10, which superimposes the average monthly discharge over the average monthly nearshore wave height. The months of June, July, and August experience relatively few closures compared to the months during the spring and fall seasons, which is counter to the common claim that inlets are most susceptible to closure during the driest months of the year. The reason for this is that the wave energy is also lowest during the summer at the Russian River. During the fall season, long-period swell waves begin to arrive at the mouth of the river. These swell waves are responsible for generating the longshore and cross-shore sediment movement in the vicinity of the inlet. Typically, regional precipitation does not increase significantly until December, which is too late to provide the river with enough water to flush out the sediment deposited by waves during the months of October and November. A relative increase in closure events observed in the months of April and May are probably a result of the discharge decreasing faster than the wave intensity. Additionally, the seasonal increase in inlet length during these months will increase frictional losses, which will weaken inlet currents and may also encourage closure. As the wave climate decreases to its lowest point during the summer, both the inlet length and the discharge in the river appear to become nearly irrelevant, and tidal fluctuations provide inlet currents strong enough to oppose the weakened wave-induced sediment transport. This suggests that closure will not occur unless the wave climate is sufficiently strong to fuel significant longshore or cross-shore sediment transport.

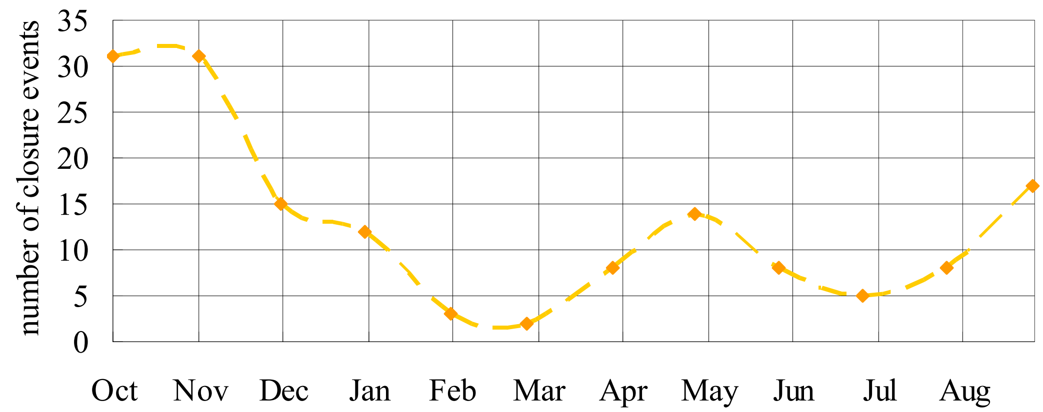

Figure 4.9. Total number of closure events by month, based on the period 1990-2006

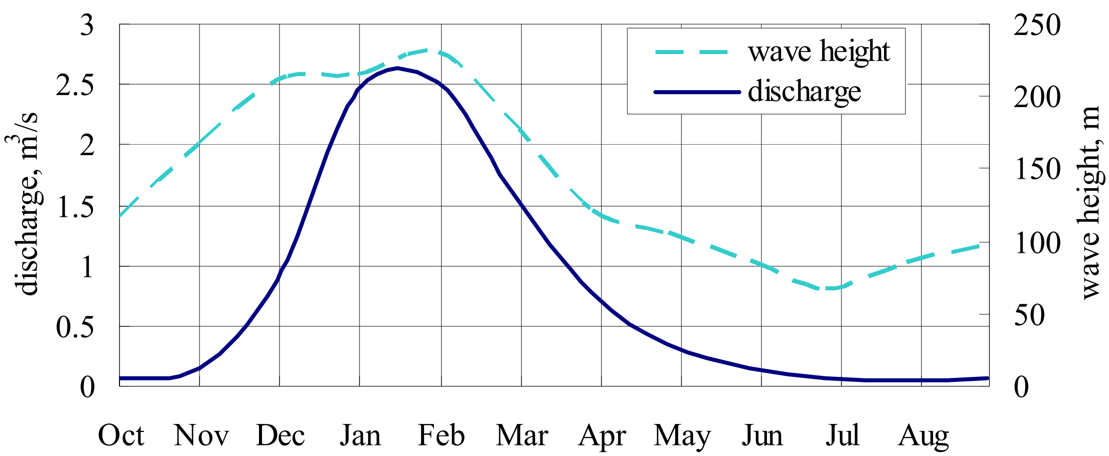

Figure 4.10. Comparison of monthly average river discharge and nearshore wave height, based on conditions from 1990-2006

The inlet geometry was found to vary strongly by season. The changes in width and length have separate explanations based on the results. Figure 4.11a shows that the seasonal increase in the average inlet width during the winter months correlates well with the rise in river discharge. High discharges cause high inlet currents and result in increased scouring and greater equilibrium areas. Depth is also likely to change with the increase in discharge, but depth measurements were not available for this study. As discharge decreases, wave height has the best correlation with the inlet width, as shown in figure 4.11b. This correlation may exist because the inlet requires a supply of sediment transported from waves to decrease in size. If the sedimentation did not require wave action, the seasonal decrease in width during the spring would likely follow the drop in discharge much more closely. Figure 4.12 shows that inlet length cannot be correlated with discharge. At the seasonal timescale, inlet length is most strongly tied to location on the barrier beach and migration history. The photographic record shows that the barrier beach is consistently widest at the northern boundary and narrowest at the southern boundary of movement and, as the mouth moves northward, the inlet lengthens to accommodate this change in width. As the inlet returns to the southern boundary of migration during the summer or fall months, the inlet channel lengthens further, following the movement of the mouth of the river.

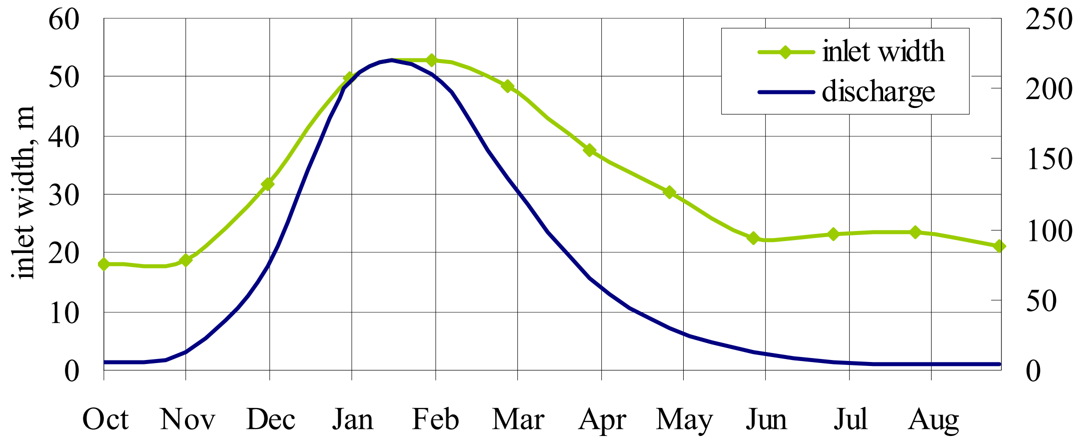

Figure 4.11a. Comparison of monthly average discharge and inlet width, based on conditions from 1990-2006

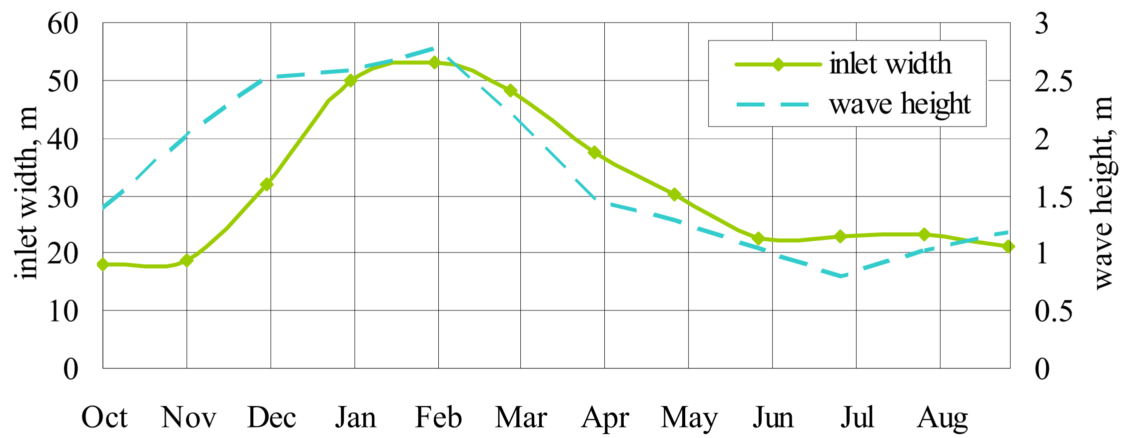

Figure 4.11b. Comparison of monthly average wave height and inlet width, based on conditions from 1990-2006

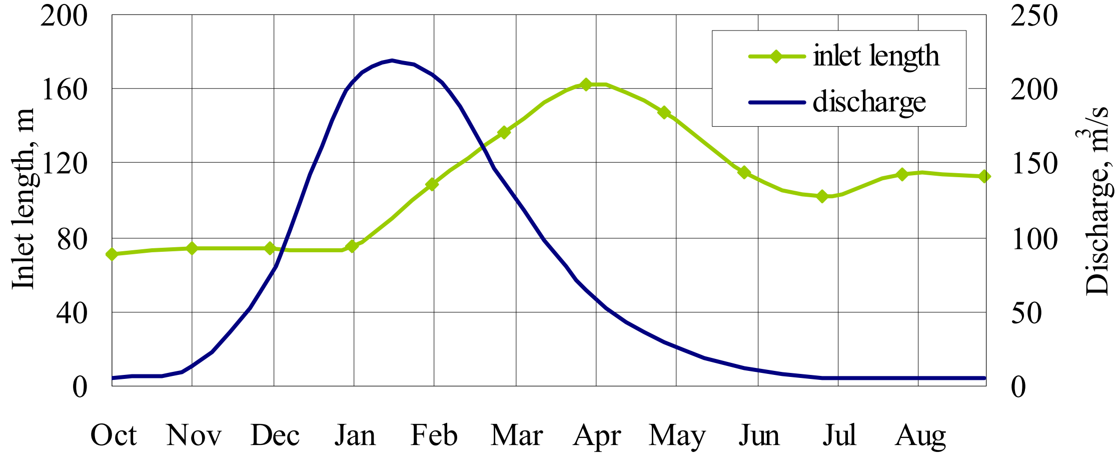

Figure 4.12. Average monthly inlet length and river discharge, based on conditions from 1990-2006.

An interesting result from this analysis was that the shape of the inlet was also found to vary seasonally. This is illustrated in Figure 4.13. The best way to explain this result is to compare the seasonal shape of the inlet with the seasonal length. According to Table 4.1, the average length for arcuate mouths is 143 meters while the average length for straight mouths is 74 meters. Somewhere between these two values, the inlet becomes long enough that it is no longer likely that it can remain perfectly straight. When Figures 4.12 and 4.13 are viewed together, they show that for months where the average inlet length is greater than roughly 100 meters, the likelihood that the mouth is straight is lower than 50%.

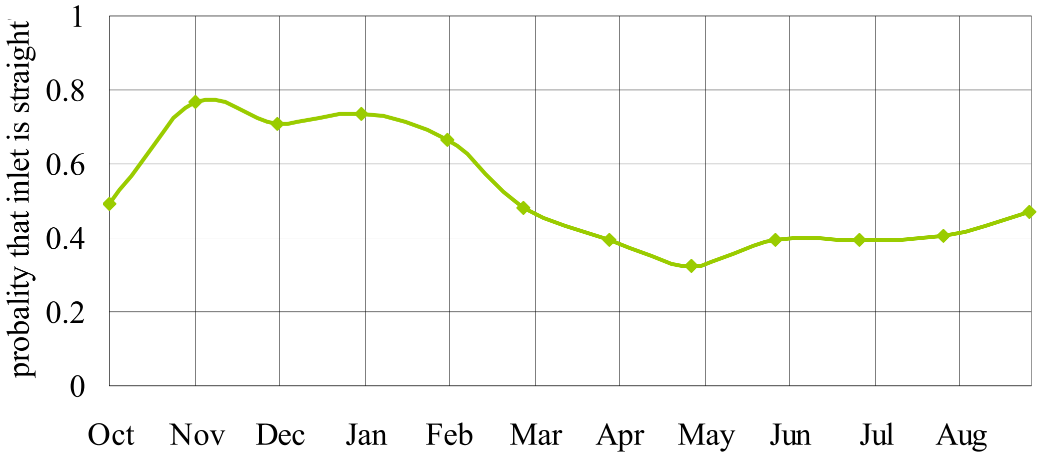

Figure 4.13. Probability that inlet is straight during each month, based on conditions from 1990-2006.

4.6.4. Behavior at the daily timescale

At the mouth of the Russian River, some of the most interesting behavior occurs at the time scale of days. Analyses encompassing entire years or seasons inevitably make tidal influence hard to see, since tidal fluctuations remain predictable and consistent over long periods of time while other processes such as discharge and wave climate may vary. An advantage of examining the inlet at a time scale of days is that the effects of tides can be seen much more readily.

The most interesting results in this analysis regard the variations of inlet width. Figure 4.14a is a comparison of inlet width, river discharge, and offshore tide range for the spring of 2003. Here, the most notable shifts in inlet width occur during peaks in discharge. However, during the summer of the same year this correlation between discharge and inlet width ceases. Figure 4.14b shows that as the discharge drops to a minimal level, the fluctuations in the inlet width correspond to fluctuations in daily tide range. This period was chosen because no closures took place during this time, and the mouth was unusually stable. In a typical year, migration of the inlet or damping of the tidal prism caused by sedimentation in the inlet make this behavior harder to see, as frictional loss and other processes start to affect inlet width as well. A more dramatic illustration of this correlation between width and tide range is provided in Figure 4.14c, which represents observations during the summer of 2001. These plots show that while both river discharge and tidal prism create inlet currents that can flush away sediment and change inlet dimensions, drastic changes in discharge appear to shift the control over inlet geometry to the tides during the driest times of the year, and to the river in seasons with more precipitation.

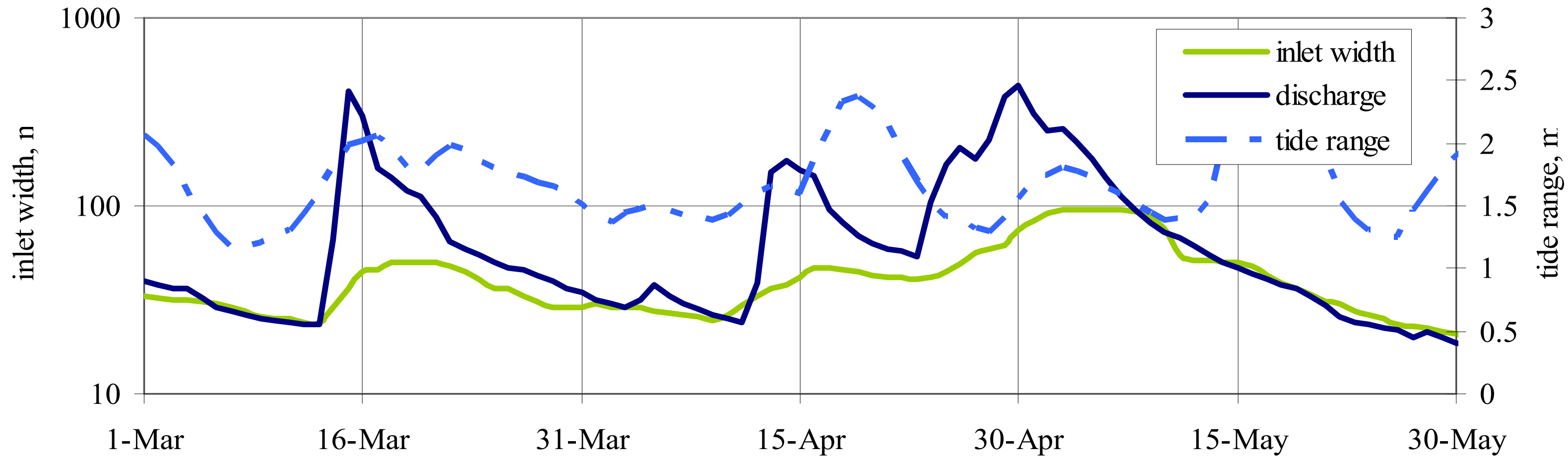

Figure 4.14a. Inlet width, river discharge, and tide range during the spring of 2002. Width values are represented as 3-day moving average values.

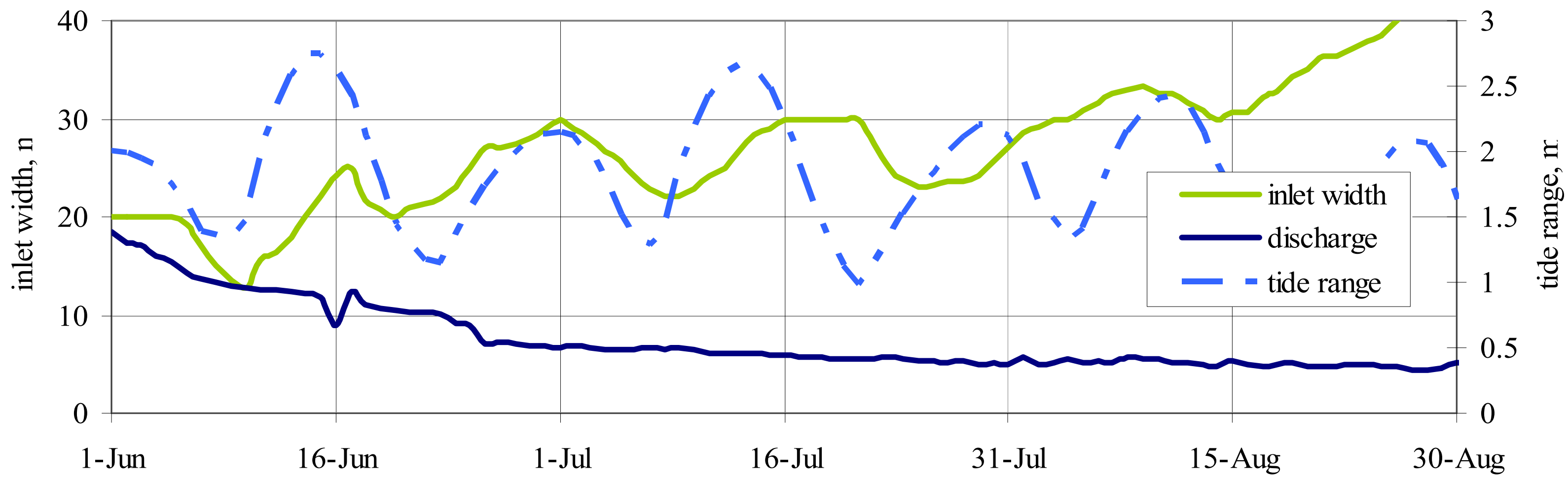

Figure 4.14b. Inlet width, river discharge, and tide range during the spring of 2002. Width values are represented as 3-day moving average values.

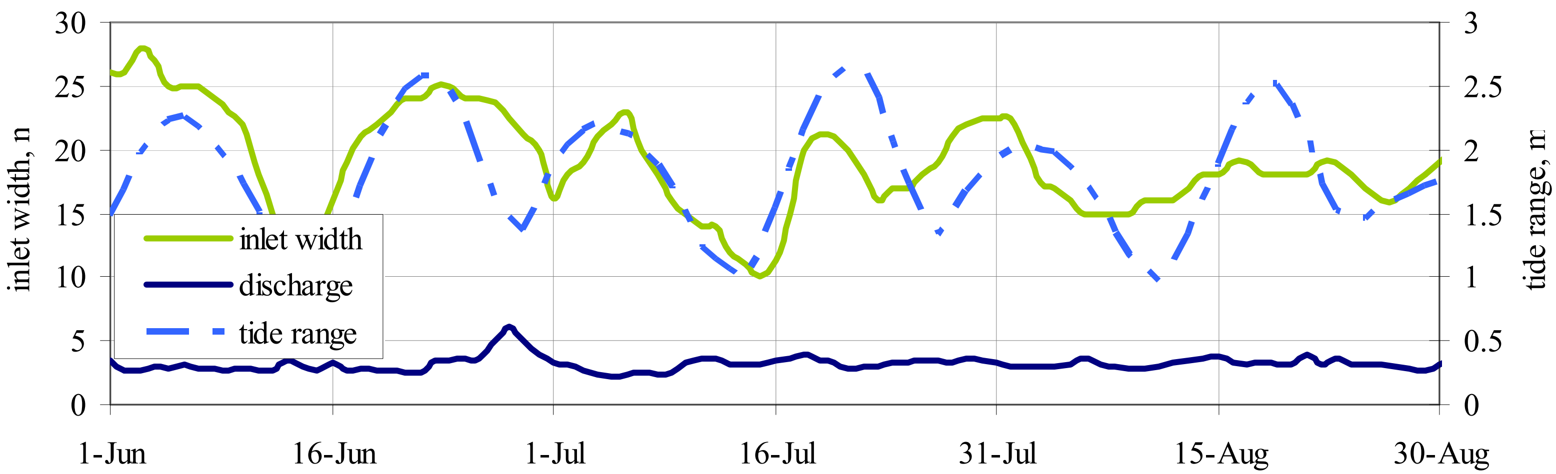

Figure 4.14c. Inlet width, river discharge, and tide range during the summer of 2001. Width values are represented as 3-day moving average values.

Variations in inlet length follow a similar pattern. While results from the analysis at the seasonal timescale show the inlet length is tied to location of the mouth on the barrier beach and migration history, the observations show that tides and discharge have an effect visible at a time scale of days. Figure 4.15a shows the length of the inlet as it varies during the spring of 2003. As with inlet width, peaks in discharge appear to cause the most drastic changes. Here, each peak in discharge is met with a corresponding drop in inlet length. Observations from the photographs indicate that this decrease in length is a result of the inlet suddenly “straightening out” or of sediment being flushed from the estuary side of the barrier beach out to the ocean. Figure 4.15b indicates that when the discharge becomes small, tides may also promote decreases in inlet length, although the shift here is much less noticeable. It appears from this plot that the lowest inlet lengths occur near the dates of spring tides (when inlet currents are highest), and that the periods in between these points are characterized by slow and steady lengthening of the inlet as longshore transport forces the mouth to migrate and extend the inlet channel.

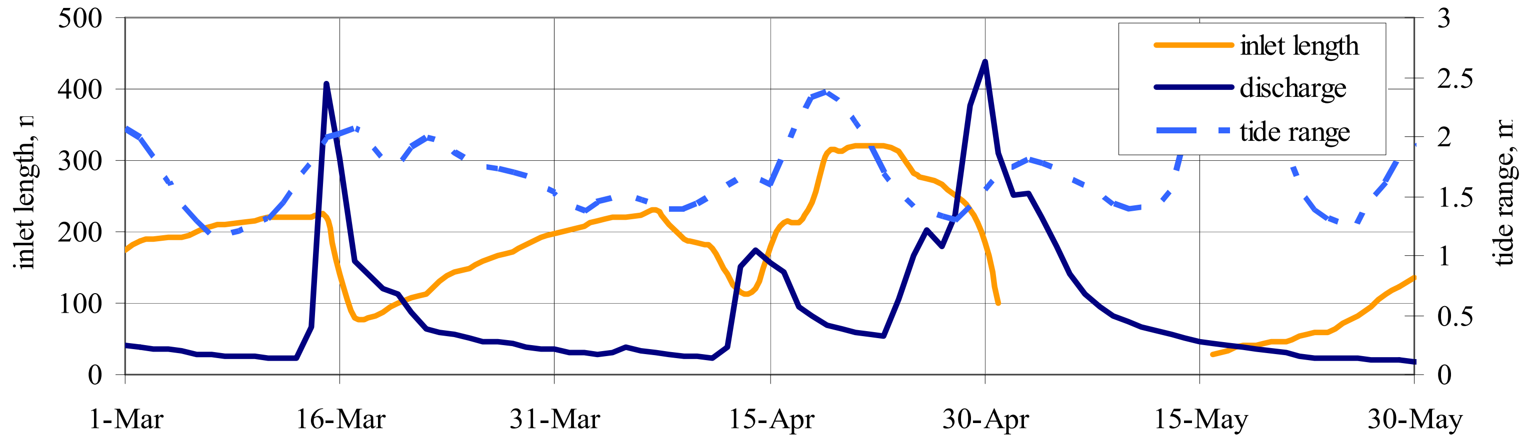

Figure 4.15a. Inlet length, tide range, and discharge during spring of 2003. Length values are represented as 3-day moving average values.

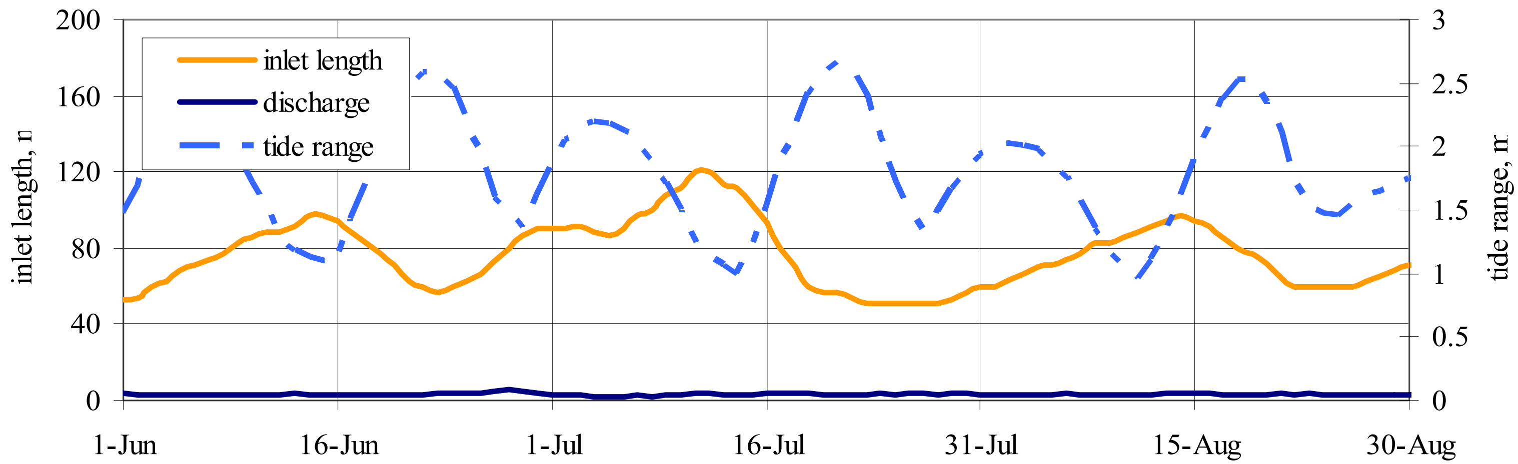

Figure 4.15b. Inlet length, discharge, and tide range during summer of 2001. Length values are represented as 3-day moving average values.

The periods after the inlet reopens following a closure event have their own distinct morphological characteristics. Changes in inlet width, length, and shape over time after breaching events were notably similar. These parameters were averaged across 50 post-breach events to provide a general idea of how the inlet evolves after communication of estuary waters to the ocean is restored. Figure 4.16a shows that after a breach, the width of the inlet initially increases substantially for several days, and then decreases to an average value over time. This initial increase in width is a response to the head difference at closure dissipating rapidly, leading to high inlet currents which decrease to more typical values over time. The plot shows that on average, sedimentation restores the width to an equilibrium value over time after this initial outburst.

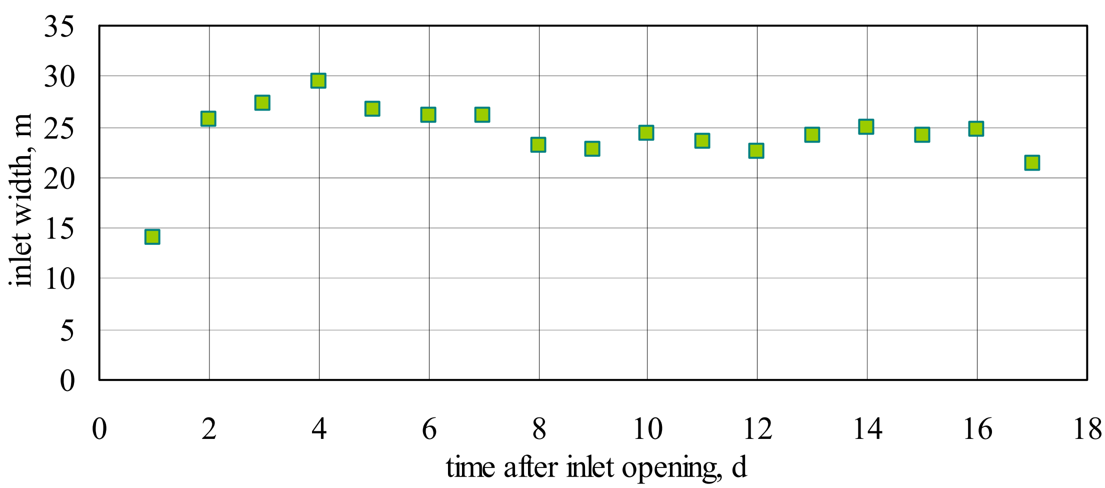

Figure 4.16a. Inlet width after breaching of the inlet mouth

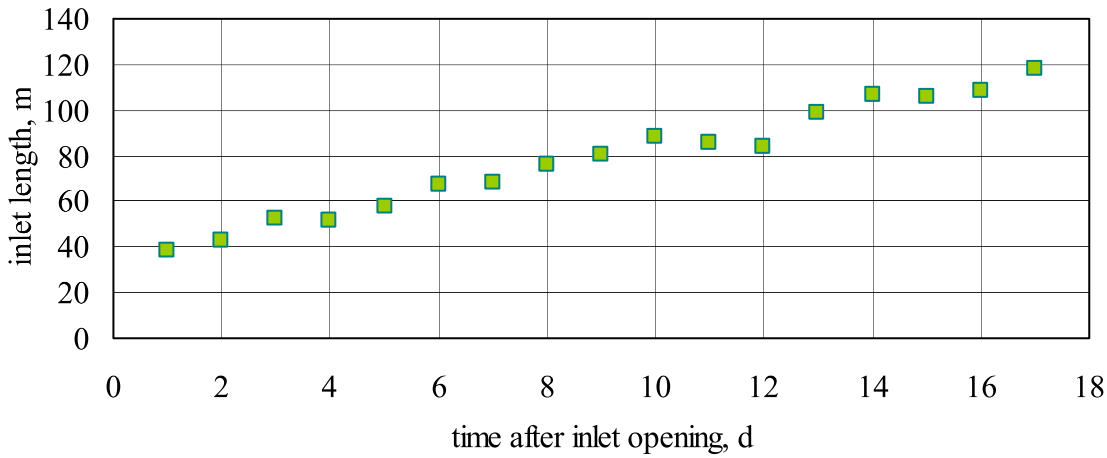

Figure 4.16b. Inlet length after breaching of the inlet mouth

The length of the inlet channel is typically much greater than its width at this site, and thus the length exhibits a much slower response to the breach event. Figure 4.16b illustrates this. On average, the inlet length steadily increases after the breach event, until a length is reached which depends on the width of the barrier beach at the location where the mouth reopened and the amount of longshore sediment transport. The shape of the inlet also exhibits a notable trend after a breach. Initially, the inlet is short, straight, and perpendicular to both the estuary and ocean side of the barrier beach. Figure 4.16c shows that the likelihood of the inlet remaining in such a straight configuration over time declines substantially. The majority of post-breach inlet configurations have some degree of curvature within only after the inlet is opened.

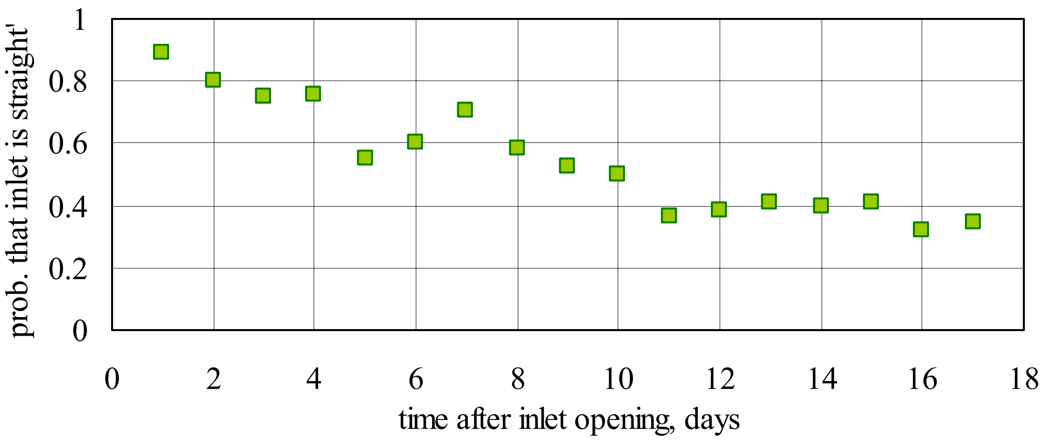

Figure 4.16c. Probability that inlet is in straight configuration after breaching of the inlet mouth

The results support the idea that a threshold indicates when the river or tides influence the size of the inlet the most. Figure 4.17a shows that when the predictive model outlined above reproduces the width based solely on tidal fluctuations in the estuary (see figure 4.4a), the highest peaks in width were overlooked, while the lower values and fluctuations in width were followed adequately. The fit based on discharge (see Figure 4.4b) behaved differently, and Figure 4.17b shows that it missed the low fluctuations in width while accurately modeling the peaks.

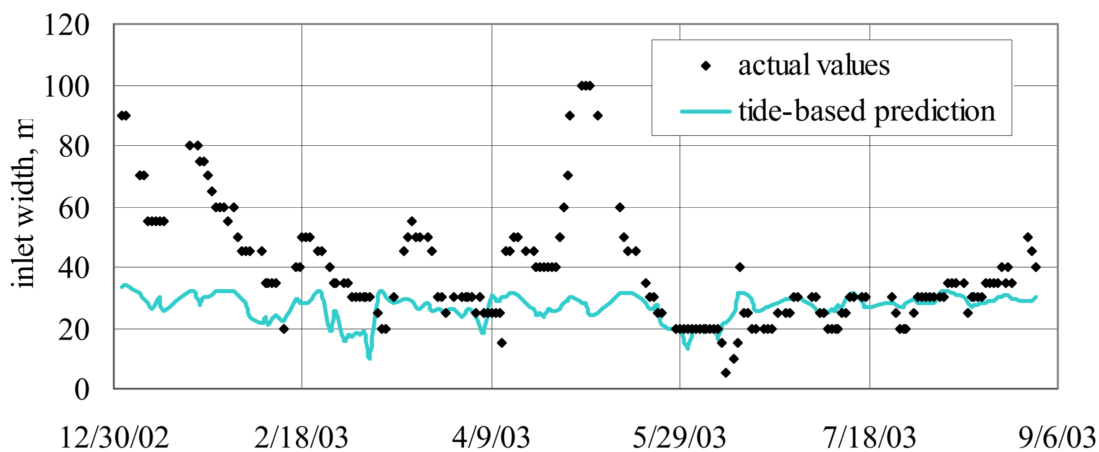

Figure 4.17a. Inlet width predictions based on a fit of the width data with estuary tide variations

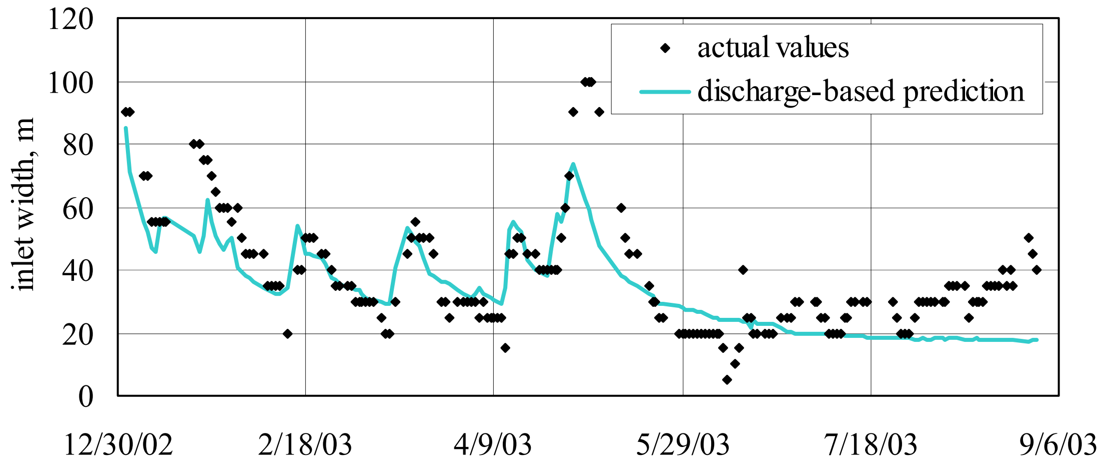

Figure 4.17b. Inlet width predictions based on a fit of the width data with river discharge

As expected, the predictions based on the threshold produced the best results. Figure 4.17c shows that separating the control over the size of the inlet width by using a threshold allows most of the actual trends to be adequately reproduced. Ideally, this analysis should be made using inlet cross-sectional area rather than width, but the results provided here still give solid evidence that a threshold exists. A constant value of 15m^3/s was used as the threshold based on the analysis of the data, but a more accurate threshold would likely consist of a ratio between the discharge volume and tidal prism during a given tidal cycle, as suggested by Komar (1996). This type of threshold would vary with time, and could potentially predict the respective roles of tides and river flow continuously. This modeling analysis has been included solely to indicate that such a threshold may exist. In this case, a more rigorous analysis would have been beyond the scope of this study, as there were many topics regarding inlet morphology to address.

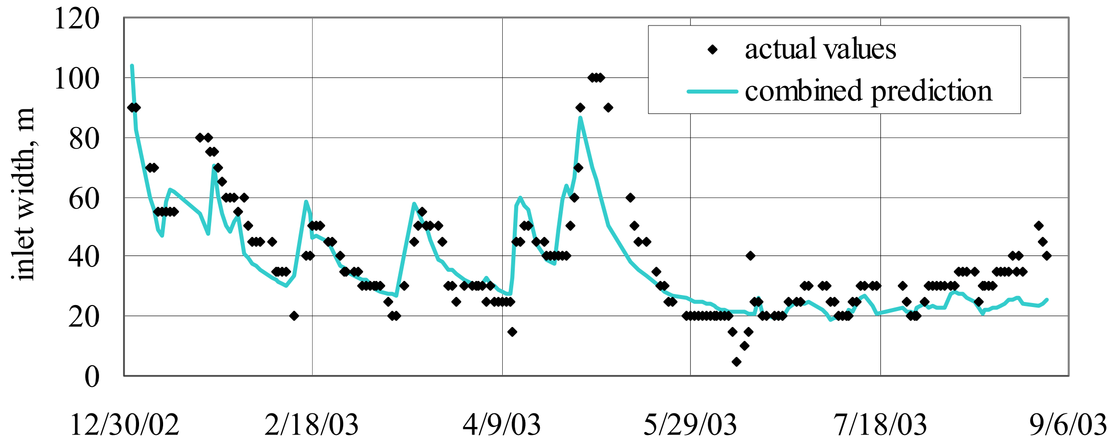

Figure 4.17c. Inlet width predictions using discharge threshold

4.7. Conclusions

The most important conclusion of this study is that the respective influence of waves, tides, and river flow vary depending on the reference time scale used in the analysis.

The results indicate that as the reference time scale decreases, the number of influential processes increases. Similarly, as the timescale increases, the influence of processes that remain roughly constant with time, such as tides, can be neglected. Table 4.4 summarizes this result for several of the characteristics analyzed in this study. The best example from this is the case of closures of the inlet mouth. The amount of time that the Russian River is closed from year to year is almost exclusively a function of the average annual discharge. This may not be the case for other estuaries, specifically on unprotected coastlines where long-term climate oscillations will effect the yearly wave climate more drastically that at the Russian River mouth. At a time scale of days, closure is caused by unequal fluctuations in discharge, tide range, and wave intensity. Also, secondary processes such as inlet configuration will increase the likelihood of closure at this timescale.

Table 4.3. Primary influences of several characteristics of the Russian River inlet at different reference time scales

Reference Timescale	Closure	Inlet Width	Inlet Length	Inlet shape
Annual	River discharge	--	--	--
Seasonal	Difference in timing of seasonal variations in river discharge and waves	River discharge	migration history, location of mouth on barrier beach	Inlet length, wave intensity
Daily	Daily variations in river discharge, tide range, and wave intensity	River discharge, tide range	River discharge, tide range, migration rate	Inlet length, wave intensity, discharge, tide range

Other factors such as seepage and evaporative losses, sediment transport rates, El Nino Southern Oscillation (ENSO), and Pacific Decadal Oscillations (PDO) were neglected

The characteristics of the inlet when it opens following a period of closure, indicate that either: (1) An equilibrium state requires both specific cross-sectional and planform geometries, which will vary depending on the location and season of the breach, or (2) dynamic equilibrium is rarely achieved here, which may be implied from the tendency of the inlet to shift from a straight configuration to a less efficient arcuate or meandering configuration over time.

The results of the inlet configuration analysis may indicate that certain local conditions such as discharge may promote configurations of a specific hydraulic efficiency, or that inlet configuration may have some role in dictating the cross-sectional and planform geometry of the inlet. It is probable that river and tide effects influence inlet geometry the most, and that the shape of the inlet has some additional influence.

Evidence was provided here that suggests the existence of a threshold which indicates whether riverine or tidal processes have more influence over the behavior of the inlet. Although a constant value was used for a threshold in this case, a threshold based on a non-dimensional number will be useful for application in other estuaries. An example of this is the ratio of river discharge volume over tidal volume during a specific tidal cycle. This type of parameter could be used to better understand the respective roles of tides and river flow for any time of the year, since it will vary continuously as discharge and tide conditions vary. It is recommended that further research in this area uses measurements of the inlet cross-sectional area rather than inlet width, length, or depth.

Chapter 5. Summary and Conclusions

The Russian River Estuary is an ideal site for a study of inlet morphology and stability in a naturally unstable system. This study is important because: (1) it can answer many questions about systems where neither tidal influence nor river flow are negligible (2) the estuary is closer to its natural state than the majority of estuarine systems in California, and (3) a wealth of data exists which can explain its inherently unstable behavior. The Russian River Estuary cannot be considered as either a tidally influenced system with negligible freshwater inflows or as a system entirely controlled by fluvial inputs. Since most studies of estuaries or lagoons focus on either of these two cases, this site provides a chance to answer many questions about the behavior of a system in which neither tides or river influence can be neglected. Such studies are surprisingly rare, and many questions about estuaries remain as a result. Additionally, unlike many California estuaries, the Russian River Estuary has resisted sedimentation, despite a history of land-use changes over the past several centuries (Goodwin and Cuffe, 1993). Therefore, the inherent instability of the inlet is more likely a result of an interaction of various natural processes than of human influence in the watershed. Lastly, the availability of an extensive dataset which illustrates the condition of the inlet for the past 30 years provides a unique opportunity to study this complex system. Readily available measurements of the river discharge, offshore wave spectra, and both offshore and in-estuary tidal fluctuations are also extremely valuable.

5.1 Closure Prediction Study

This study tested the applicability of a non-dimensional predictor of inlet stability. A method introduced by O'Brien (1971) was modified. The objectives of the study were defined as follows:

1. Test inlet stability models to see if inlet closure can be predicted in estuaries with significant freshwater inflows, using the Russian River Estuary as a case study.
2. Use these models to indicate the relevance of each of the major processes involved in either stabilizing or closing the inlet.

Inlet width measurements were necessary to calculate the tidal influence. Rather than assuming a constant width, estimations were made by analyzing the provided photographs of the inlet and comparing its dimensions to known distances between other visible objects on the barrier beach. The shallow water assumption was used to simplify the wave group speed near the mouth. Also, measurements made in the estuary by Goodwin and Cuffe (1993) were used to quantify the tidal prism. A value was assumed for the bottom slope of the inlet channel. The period from June 17, 1999, to December 31, 2006 was used for the analysis, since there were no gaps in the available data for this period of time. In total, the closure record during this period was reproduced using a total of five different models, and results were compared to actual observations of closure events. Results were analyzed in two separate ways: (1) the maximum possible number of correct predictions were produced for each of the study methods without putting a limit on the number of incorrect predictions produced, and (2) the maximum possible number of correct predictions were produced when placing a limit of either 10 or 20 incorrect predictions. This was necessary since several models produced nearly equal amounts of correct predictions, but varied widely in the amount of incorrect predictions produced.

The best predictive results were achieved by modifying O'Brien's original stability index to include a term accounting for river influence. This method (Proposed Method 3) differed from a similar approach by Goodwin (1996) by defining the river influence term as a function of bottom slope, rather than a ratio of tide range to inlet width. Discharge, tides, and waves were all shown to be important, since the model that performed the best included all of these influences. A sensitivity analysis showed that near-shore wave estimates provide more accurate results than offshore measurements, and that varying the slope or the incoming group speed of waves did not significantly change the model's ability to accurately predict closure. Surprisingly, offshore tide measurements produced more accurate model predictions than in-estuary tidal fluctuations. This may result from river influence over the low water level in the estuary, which makes calculations of the effective tide range smaller than real values. The range of days before and after actual closure events for which predictions were considered "correct" also effected the accuracy of the methods used in this study. Ultimately, the most accurate method predicted more than 80% of the closure events during the study period while only producing a minimal amount of incorrect predictions.

Three-dimensional models which account for all of the relevant processes will likely produce the most accurate predictions of closure. The methods tested in this study are much simpler and less computationally expensive than numerical models, but they are not assumed to be more accurate. Further testing in other estuaries is needed to justify their use as management tools.

5.2 Morphology Study

This study expounded on the findings of Byrne and Gammisch (1980), who noted that small inlet systems behave differently than the large tidally dominated systems studied by O'Brien (1931, 1969) and Jarrett (1976). The objectives were defined as follows:

1. Gain an understanding of the relationship between external forcing from tides, waves, and river discharge and morphological response observed at the Russian River inlet.
2. Investigate the behavior of this system at annual, seasonal, and daily timescales.
3. Find evidence that a threshold may exist which dictates whether the river or tides control the morphology of the inlet.

This study required the quantification of inlet characteristics available from the provided photographic record. The positions of objects on the barrier beach were visible in the photographic record, as well as in satellite images available through GoogleEarth. The width and length of the inlet were quantified by noting their relative size compared with known distances between the objects on the barrier beach. Also, the shape of the inlet was obtained from the photographs, as well as the position of the inlet within its bounds of migration.

The study found that the closure habits and geometric characteristics of the inlet exhibit different behaviors when observed at different time scales. The degree to which the dominant processes (wave-induced sediment transport, tidal fluctuations, river discharge) remain constant over time affected their respective influences over the inlet at different time scales. For example, tides, which change very little with each year, were only influential in governing closure habits at the daily timescale. Waves, which can change slightly in intensity from year to year, were important at the daily and seasonal timescales. At the annual timescale, only the river discharge, which sharply fluctuates from year-to-year, had any influence over the yearly closure habits. Additionally, several configurations (shapes) of the inlet were tied to specific risks of imminent closure and different characteristic discharges and inlet geometries. Finally, it was verified that a threshold exists which indicates whether the river or tides have more influence over the response of the inlet at any time.

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