Crissy Field Marsh Expansion Study

FINAL REPORT

Prepared by

Philip Williams & Associates, Ltd.

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PWA REF. # 1623

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1. INTRODUCTION AND BACKGROUND

1.1 SITE HISTORY

Historically, Crissy Field and the Marina Green were part of an extensive 127-acre backdune marsh that drained the Tennessee Hollow watershed to San Francisco Bay. Aeolian (sand-driven) transport from the west formed a sand spit to the east, and the mouth of the 150 ft wide entrance channel was located close to Marina Beach and sheltered from the predominant northwesterly waves. Anthropogenic changes to the wetland coincided with development of the Presidio, and the marsh was completely filled for the Panama-Pacific International Exposition of 1915. The marsh site was transferred to the National Park Service (NPS) in 1994, when the Presidio became part of the Golden Gate National Recreation Area (GGNRA). In November 1999 tidal action was introduced into a restored tidal marsh at Crissy Field.

Although a 30-acre footprint was initially recommended as the minimum size required to maintain natural functioning of a tidal backdune marsh, other constraints on the site limited the area of the tidal marsh to about 20 acres. Recognizing the increase in closure potential due the smaller footprint, the tidal prism was increased by expanding the relative area of sub-tidal habitat. The morphological response of the system was rapid, with flood- and ebb-tidal shoals developing at the landward and bayward ends of the inlet, respectively. Risk of closure increased as sand deposition in the channel and flood shoal continued, and in May 2001 natural closure and breaching occurred. The inlet channel has continued to close and re-open intermittently, with one unauthorized mechanical breach in the winter of 2001-2002 and a NPS breach in March 2003.

1.2 PROJECT OBJECTIVES

Per the request of the Presidio Trust, and in cooperation with the GGNRA and Golden Gate National Parks Conservancy (Parks Conservancy), Philip Williams and Associates, Ltd. (PWA) was hired to re-evaluate the relationship between marsh area and inlet dynamics. In particular, this study was to review and if necessary revise the estimate of the minimum area required to maintain continuous tidal function. The study also was to evaluate the potential for closure for an incrementally enlarged wetland. This study relies heavily on monitoring data collected over the past 2½ years by PWA and GGNRA/Parks Conservancy. The following sections summarize the approach we have adopted in estimating the potential for closure of the tidal inlet at Crissy Field and the results.

2. CONCLUSIONS AND RECOMMENDATIONS

As part of the present study, monitoring data collected from May 2001 through September 2002 were reviewed to improve our understanding of the morphological and hydrodynamic processes of the Crissy Field Marsh. Additionally, 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 model is not a precise engineering tool that explicitly simulates the sediment transport processes. Instead, the QCM is based on simple stability criteria, our understanding of the closure and breaching mechanisms, and easily computed parameters such as wave and tidal power as surrogates for complex sediment transport processes at the inlet. The model retains enough accuracy to be a useful tool for planning purposes. Application of the QCM to existing conditions resulted in the model simulating most (10 of the 13) documented closures over the 17-month period from 4/15/2001 to 9/31/2002. Results from this analysis lead to the following conclusions and recommendations.

Conclusions:

- Morphological evolution of the marsh-inlet-beach system through May 2001 has been documented in previous reports (PWA, 2001a; PWA, 2001b), but review of more recent monitoring data has improved our understanding of the inlet morphology and dynamics. The system appears to be in dynamic equilibrium, with the marsh presently in its transitional state as a mesotidal sandy coastal lagoon. Based on the limited amount of estuarine sedimentation data to date, we expect the site to maintain its present condition as an open water lagoon subject to intermittent closures for several decades.

- Inlet closure and breaching conditions have been quantified. The risk of closure is primarily driven by the joint probability of waves and tides, and depends parametrically on the size of the lagoon. Closures usually occur during neap tides when tidal scour is minimal. Natural re-opening typically occurs during the following spring tides, after inundation from the Bay increases water levels in the lagoon and surface flow during the ebb tides scours a new channel, typically near the location of the remnant inlet mouth.

- The maximum thalweg elevation of the inlet controls the low water elevation in the lagoon, and significantly affects the stability of the inlet. Monitoring data show that the high point of the thalweg usually occurs as it passes over the flood shoal, and that evolution of the shoal coincided with the reduction of inlet stability. Application of the QCM reveals that the ability of expanded wetlands to remain open is very sensitive to the low water elevation in the marsh. A key issue in applying the QCM to expanded wetland sizes was estimating the maximum thalweg elevation for these hypothetical cases. Under present conditions, sheet flow over the sandy flood shoal dominates. However, over the long-term, channel morphology may change and lower the thalweg elevation if cohesive material deposits replace sand in the flood shoal.

- Over the long-term, the effective tidal prism may diminish as estuarine sediments fill the sub- and inter-tidal areas of the lagoon and a vegetated marsh develops near Mean Higher High Water (MHHW), acting to reduce the natural scouring potential along the entrance channel. Presently, there is not enough monitoring data to establish precise estimates of sedimentation in the lagoon. In addition, other factors that will influence the character of the evolved site complicate a quantitative prediction of exact morphology. These include: local wind-wave action in the lagoon that may limit the aerial extent of high marsh; the accelerating rate of sea level rise; and, changes to the inlet morphology as cohesive estuarine sediments are deposited over the flood shoal and entrance channel. Application of the QCM indicates that the long-term stability of the inlet channel will be strongly influenced by the low water elevation in the fully evolved state.

- Based on our QCM analysis, continuous tidal action could be achieved over a typical year if the lagoon diurnal tidal prism were increased from its present value of 17 acre-feet (ac-ft) to approximately 56 ac-ft. Since the frequency of inlet closure is related to tidal prism intermediate wetland sizes are expected to experience intermittent closures, although less frequent than the existing Crissy Field marsh. For example, we expect an expanded lagoon with 39 ac-ft to close about once per year under typical wave conditions. These predictions are based on average wave conditions, and more frequent inlet closure is expected during unusually high energy wave events.

- Future expansions to the existing marsh should include enlarging the area near the flood shoal in a radial direction so that increases in its current footprint would not reduce tidal circulation by “pinching” off the southeast portion of the lagoon near the footbridge. Circulation in this area is of particular concern due to the 72-inch outfall that discharges stormwater into the lagoon. Poor circulation could reduce the effective tidal prism as well as worsen water quality in areas of the lagoon where tidal exchange is low. Marsh expansion near the flood shoal would tend to mitigate these effects.

- The precise geometry of an expanded wetland needs to be studied further, although some general comments regarding its planform and vertical profile can be made. Firstly, major excavation below the expected low water elevation would not increase the effective tidal prism or improve the stability of the inlet, and some cost savings may be realized by limiting excavation at or above this elevation. Secondly, expanded wetlands with low-gradient sides could increase ecological values by creating more mid and high marsh area, although this would require larger marsh area. However, low-gradient sides would require larger marsh area than steep sides in order to develop the same tidal prism.

- Temporary and long-term changes to the morphology of East Beach are expected following wetland expansion. Increases in the volumes of the ebb- and flood-tidal shoals will disrupt the delivery of sand east of the inlet until a new equilibrium is reached, and may lead to temporary loss of beach width. Some of the expected loss of beach width will be recovered as natural sand by-passing increases after the ebb bar matures, but other long-term changes to the shoreline along East Beach may result in response to the new wave and tidal regimes that will occur under expanded wetland conditions.

Recommendations for additional study:

- Empirical relationships between throat morphology, shoal/thalweg elevation, lagoon area, and tidal prism are lacking for sandy coastal lagoons such as Crissy Field. Field data could be collected from reference sites to establish such relationships. This would refine the estimates of thalweg elevation for expanded wetland sizes – a key issue in apply the QCM to hypothetical cases.

- Improvements in the wave transformation matrix will refine the estimates of nearshore wave power and reduce the uncertainties in the QCM. Ideally, fully directional offshore wave spectra should be used to re-construct a revised transformation matrix.

- The wave record from the Point Reyes buoy limited the duration of the QCM simulations to about six years. Longer records of historical offshore wave data from the Monterey buoy could be re-formatted for input into the QCM, or a new wave transformation matrix could be constructed, for longer model simulations. This would refine estimates of the frequency of closure by including more infrequent wave events in the analysis.

- NPS should continue ecological monitoring at Crissy Field, which will inform the acceptable duration of inlet closure. Adequate tidal functions may not require a continuously open inlet, however a self-maintaining system may be desirable from a management perspective.

3. GOALS OF THE CRISSY FIELD MARSH

Future expansion of the marsh at Crissy Field should aim to achieve the overall goals of the approved Crissy Field Plan and Environmental Assessment (Jones & Stokes Associates, 1996). The goal for Crissy Field as articulated in the Crissy Field Plan is to "enhance the setting for recreation and visitor enjoyment while rehabilitating and preserving important historic resources and natural values."

The desired natural values of the marsh were described in Objective 2: "Enhance and expand existing natural resource values and capitalize on opportunities to restore dunes and a remnant of the historic tidal marsh. This objective includes:

- Re-establishing an ecologically viable self-sustaining tidal marsh requiring a minimum of human intervention and providing high-quality educational and interpretive opportunities;
- Providing for connection of the future restored riparian corridor to the marsh and allowing for future expansion of the marsh south of Mason Street;
- Restoring and enhancing native plant communities, expanding the native dune community to allow viable biological and coastal processes to occur, removing non-native vegetation, and providing access through sensitive dunes along designated paths; and
- Providing adequate protection for wildlife currently on the site and anticipated to occur as a result of planned improvements."

Based on the overall goal for Crissy Field and the objective defined for the marsh, three primary goals were identified for this study:

1. Tidal restoration and associated ecological functions are a primary goal.
2. Development of a self-sustaining marsh in the short- and long-term. Closure frequency and duration may change as siltation occurs, and the criteria for mechanical breaching should be applicable to the early and mature stages of the site.
3. The tidal restoration should accommodate existing recreational uses at East Beach.

The purpose of the present study is to determine the minimum tidal prism required to maintain continuous tidal action to the Crissy Field marsh, as well as to estimate the frequency and duration of inlet closures under intermediate wetland sizes. This information will help inform decision makers during later planning stages in order to increase the probability of meeting the goals and objectives articulated in the Crissy Field Plan.

4. A CONCEPTUAL MODEL FOR CRISSY FIELD

4.1 EVOLUTION TOWARD A DYNAMIC EQUILIBRIUM

In general, the marsh-inlet-beach system evolved rapidly during approximately the first 18 months following restoration but is now close to a dynamic equilibrium and in its transitional state as a sandy coastal lagoon. Development of the flood- and ebb-tidal shoals significantly reduced the effective tidal prism by the spring of 2001, resulting in the first inlet closure in May of that year. The system appears to be close to a dynamic equilibrium since then, with reduced rates of sedimentation over the shoals, intermittent closures and re-opening, and a seasonal cycle of channel migration.

The paragraphs below describe, at a conceptual level, the hydrodynamic and geomorphic evolution of the site since the introduction of tidal action in November 1999. A brief summary of the stability of the tidal inlet is also presented. Much of the material presented in this and subsequent sections relies on data collected by PWA and GGNRA as part of the physical monitoring program shown in Figure 4-1.

4.1.1 Lagoon Hydrodynamics

Immediately following restoration, tidal exchange in the marsh was strong due to the lack of tidal shoals and a hydraulically efficient connection to the Bay. As shown in Figure 4-2, the water level in the marsh initially drained to about –1 ft NGVD, resulting in a diurnal tidal prism of approximately 40 ac-ft. The tidal range in the marsh was significantly reduced as the flood shoal evolved, and by May 2001 the low water elevation was about +1.5 ft NGVD, resulting in an effective mean diurnal tidal prism of approximately 17 ac-ft and the first inlet closure. In general, muting has limited the lagoon tide range to the upper fourth of the Bay tide range (Table 4-1) and significantly limited the amount of potential tidal prism that is mobilized.

Table 4-1. Tidal Datums for San Francisco Bay

Tidal Datum	Elevation (ft)	
	NGVD	MLLW
MHHW	+2.98	+5.83
MHW	+2.38	+5.23
MTL	+0.33	+3.18
MLW	-1.72	+1.13
MLLW	-2.85	0.00

MLLW to NGVD conversion from National Geodetic Survey (NGS)
Tidal Datum Elevations from NOAA station 9414290 (Presidio gage)

The hydrodynamic response to the morphology of the inlet is clearly evident from Figure 4-2, which plots the water level in the lagoon and the maximum thalweg elevation along the inlet channel. This high point in the channel thalweg typically occurs as the channel crosses the flood shoal, and controls the low water elevation in the marsh. An unplanned mechanical breach on January 16, 2002 re-established an efficient connection to the bay, and tidal exchange improved until sedimentation returned the low water elevation to its pre-breach levels.

4.1.2 Morphological Changes

The morphology of the marsh-inlet-beach system evolved rapidly after restoration, in response to the strong supply of littoral sediments and relatively large effective tidal prism. The sequenced aerial photographs in Figure 4–3 show the formation of the flood- and ebb-tidal shoals, migration of the inlet channel, and erosion of the downdrift beach width. By the spring of 2001, the sedimentation rate over the flood shoal diminished and ebb shoal growth was limited primarily to extending eastward to East Beach, with its volume stabilizing one year later (see Figure 4–4).

The inlet channel gradually migrated to the east due to the predominant eastward longshore sand transport and reduced effective tidal prism of the maturing lagoon. Monitoring data reveal that the channel also breaks out at locations depending on environmental conditions, and that the channel alignment fluctuates within an envelope of locations. The plan view of the inlet channel collected during surveys since 2001 are plotted in Figure 4–5, and show a cycle of east-west migration. The alignment of the inlet channel falls into one of three distinct groups: a high-efficiency alignment following mechanical breaching of the inlet; a medium-efficiency alignment in which the inlet drains the northeast; and a low-efficiency alignment with the mouth of the inlet located east of the outfall pipes on East Beach.

The profiles of these inlets are plotted in Figure 4–6, and a correlation between channel length and maximum thalweg elevation is evident in Figure 4–7. Transects of beach profile 14-E are plotted in Figure 4–8 and show an elevated beach berm during the low-efficiency channel alignments. The morphology of the beach changes in response to the intensity of the wave conditions, and when the channel is in its medium-efficient alignment the elevation of the berm is reduced to inter-tidal elevations.

4.1.3 Inlet Stability

As the marsh evolved during the first 18 months following restoration of tidal action, the scouring action of ebb tidal currents in the inlet channel was reduced as the effective tidal prism decreased. The inlet first closed and naturally re-opened in May 2001. Since the site has reached its present state of dynamic equilibrium as a sandy coastal lagoon with more fully developed tidal shoals, the inlet has undergone a series of intermittent closures and breaches, as listed in Table 4-2. The inlet typically closes during neap tides when tidal power is at a minimum, and naturally breaks out during spring tides when water levels in the bay exceed some critical elevation in relation to the beach barrier.

Table 4-2. Observed Closure Events at Crissy Field

Event	Dates	Comment
1	5/1/01 – 5/4/01	Intermittent closures and mechanical breaches during neap tides.
2	5/12/01 – 5/20/01	Neap closure and natural re-opening during rising spring tides.
3	6/14/01 – 6/16/01	Neap closure and natural re-opening during rising spring tides.
4	unknown – 8/16/01	No field data during closure, only natural breaching during rising spring tides.
5	10/21/01 – 11/5/01	No field data but confirmed by NPS staff.
6	11/21/01 – 11/24/01	High swell during neap tides closed inlet. Unusually high tides breached inlet.
7	12/5/01 – 12/14/01	Partial closure (tide range < 0.5 ft).
8	12/14/01 – 12/28/01	Full closure during spring tides due to low effective tidal prism. Re-opening during unusually large tides.
9	1/2/02 – 1/16/02	Closure due to reduced effective tidal prism. Unplanned mechanical breach.
10	7/1/02 – 7/8/02	No field data but confirmed by NPS staff.
11	7/31/02 – 8/6/02	Neap closure and natural re-opening during rising spring tides. Run-up over ebb shoal raised during closure.
12	8/27/02 – 9/4/02	Neap closure and natural re-opening during rising spring tides.
13	9/21/02 – 10/9/02	Partial then full closure and spring breaching. Photo-documentation of run-up over ebb shoal prior to breach. No field data.

Note: Closure is defined as lack of discharge from Crissy Field (i.e., no reduction in lagoon water levels) during falling ebb tides in the bay. Partial closures were defined as periods when drainage from the lagoon was significantly reduced and water levels in the wetland drained less than half a foot over tidal cycle.

Two notable exceptions to the natural re-opening process are the mechanical breaches of early May 2001 and the unplanned breach of January 2002 (the inlet was mechanically breached a third time by the NPS in March 2003, but this event occurred after the QCM calibration period). In the first instance, NPS staff intervened repeatedly but was unable to maintain continuous tidal action due to the low scouring power of coincident neap tides. The unauthorized mechanical breach of January 2002 followed a series of winter storms that created a substantial barrier between the lagoon and the bay. Scour rapidly enlarged the small hand-dug breach due to the large amount of water stored in the lagoon and relatively calm seas, resulting in an efficient channel and continuous tidal action for several months.

4.2 A CONCEPTUAL MODEL OF INLET DYNAMICS

PWA developed a conceptual model of the tidal inlet at Crissy Field by examining survey data, observing the site, and applying our understanding of the physical processes associated with lagoon opening and closures. A description of that conceptual model, particularly the mechanisms that induce closure and breaching, is given below.

4.2.1 Closure Mechanisms

The ability of an inlet to remain open is primarily a function of the scouring effect of tidal currents and the amount of sediment deposited near its entrance due to wave-induced sand transport. An inlet will close if currents in the channel are not sufficiently strong to scour away material that has been deposited near the mouth. Closure usually occurs during neap tides, when the scour potential along the channel is minimum. However, antecedent channel morphology and the intensity of the coincident waves also contribute to the closure potential. The following three different mechanisms appear to lead to closure at Crissy Field due to the variable wave climate and inlet morphology.

- Elongated Inlet Channel and Small Seas Hydraulic efficiency of the inlet is reduced as the maximum thalweg elevation increases and the channel migrates toward the east. As described above, this channel morphology is generally associated with the berm-type beach profile that typically develops during the summer and autumn. Although the loss of energy available for keeping the inlet open is most strongly influenced by the smaller effective tidal prism, friction losses along the elongated channel also play a role. This decrease in scour potential makes the inlet less stable, and relatively small seas are able to induce closure. An example of this elongated channel-small sea mechanism is the closure of May 12, 2001. The survey of the channel thalweg carried out on May 11, 2001 shows that the inlet was in its low-efficiency alignment and draining to the east (Figure 4–5). The wave power at Crissy Field was relatively mild, but strong enough to affect the channel in its elongated and inefficient state. Incomplete filling of the marsh during high tides on May 11th preceded inlet closure the next day (Figure 4-9).

- High Swell and Neap Tides Closure also occurs when the channel is in its medium-efficiency alignment, but requires greater wave-driven sand transport since the inlet is generally more stable (wind-driven sand transport is secondary, but also affects the closure potential). Neap tides reduce the scour potential on a fortnightly basis, and the risk of closure is determined by the joint probability of these low tides and sand deposition during a high swell event. An example of high swell-neap tide mechanism is the closure of November 21, 2001 (Figure 4–10). A survey in mid-October, 2001 indicates that the channel was in its medium-efficiency alignment and draining to the northeast (Figure 4–5). Strong waves on November 21st coincided with neap tides, and the inlet closed rapidly.

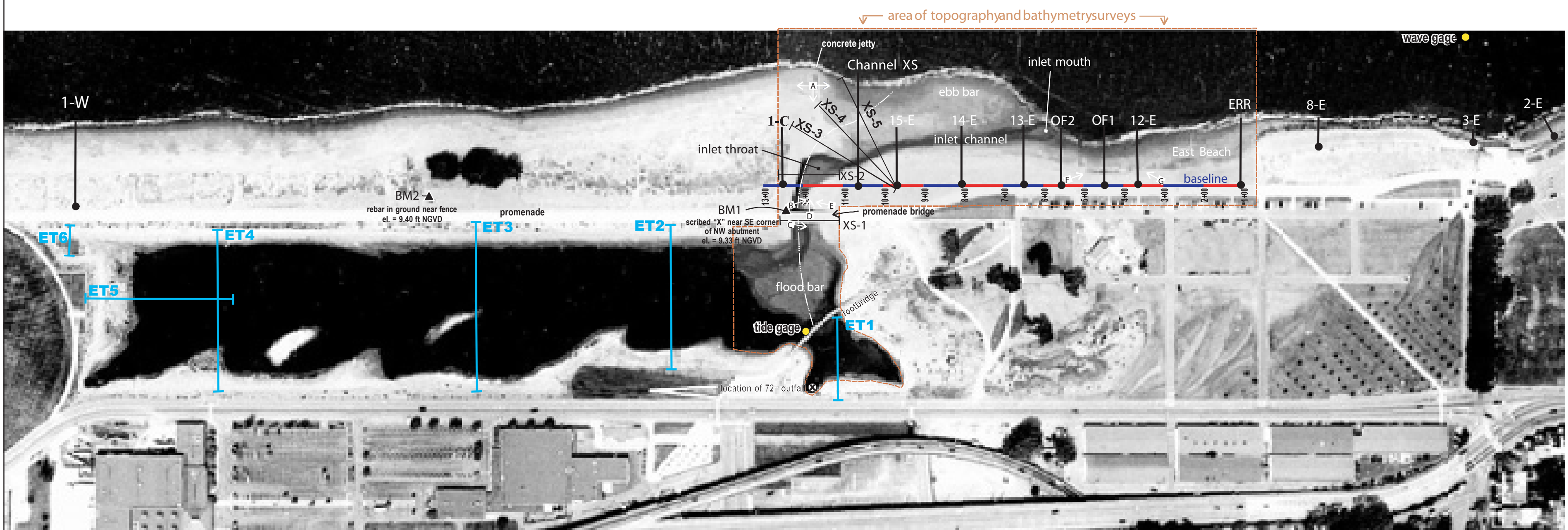
- Very Large Swell with Neap or Spring Tides Very strong waves may deposit enough sand in the mouth to close the inlet irrespective of the spring neap tidal cycle or alignment of the inlet channel. In this case the scouring potential of the tides, even spring ebb flows, is not strong enough to remove the large amount of sediment deposited in the entrance channel during the preceding flood tide.

4.2.2 Breaching Mechanisms

Natural re-opening of a closed inlet occurs when the water level on one side of the beach barrier exceeds some critical elevation, with duration of higher water also contributing to the breaching potential (Kraus, 2002). Surface flow scours a channel and the inlet breaks out at the lowest point along the beach barrier. This breaching mechanism is complicated by the wave run-up, storm surge, antecedent topography of the beach barrier, and the storage capacity of the lagoon. At Crissy Field natural breaching occurs from overtopping of the beach barrier from the bay side (foreshore) since the relatively small watershed area contributes a relatively little freshwater to the lagoon. Figure 4–11 shows this inundation process, at a conceptual level, during periods of closure. Since overtopping of the berm crest only occurs at high tides, the period of inundation is typically limited to the few hours immediately before and after higher high water.

Photo documentation collected during the afternoon of October 9, 2002 (Figure 4–12) illustrate the mechanisms that lead to natural breaching of the closed inlet. Wave run-up washes over the beach berm and inundates the closed inlet channel during high tides in the bay. This process that can significantly raise the lagoon water levels over a period of several days. If the duration of inundation is sufficient to raise water levels in the lagoon above some critical elevation, the remnant channel will break out at the lowest point along the barrier as the marsh begins to ebb. Seepage flow has been observed during periods of closure (Figure 4–13), which sometimes maintains a 'low spot' in the beach berm at the prior mouth location. Scour during the falling ebb tides rapidly forms a new channel and re-establishes tidal action to the marsh.

The elevation of the beach berm relative to the water levels in the bay affect the duration of inundation and amount of water added to the marsh. Wave run-up is also a contributing factor. Depending on the initial water level in the lagoon and its stage-storage characteristics, several episodes of inundation during higher high water may be required until conditions are sufficient to scour a new inlet channel during the following ebb tide. This is particularly true if the inlet closed during neap tides and water levels in the lagoon are relatively low. Monitoring data (Figure 4–14) show that the breach on August 6, 2002 was preceded by five episodes of inundation during relatively weak neap high tides. Inundation was more substantial as the spring tides approached, and surface flow was sufficient to scour a new entrance channel during the dominant ebb tide of August 6th.



▲ = benchmark

A→ = photodocumentation station

● = tide gage

12-E = beach profile

XS 2 = cross sections

= thalweg profile

= marsh elevation transect

= baseline

N

0 300 600

approximate scale in feet

figure 4-1

Crissy Field Marsh Expansion Study

Location of Monitoring at Crissy Field

date of photo: 4/2/2001

Survey control provided by Towill

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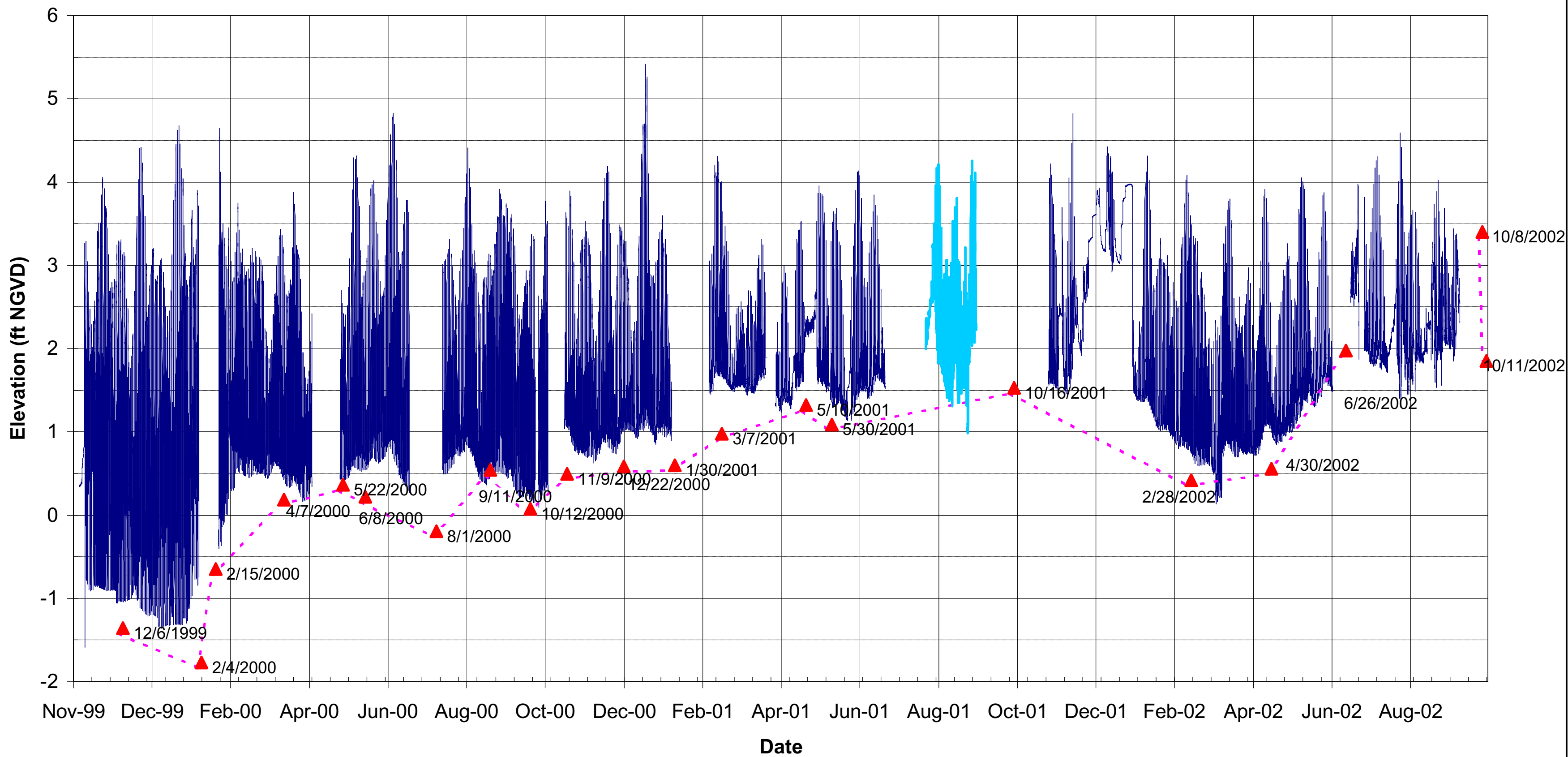
PWA



Source: Tides from GGNRA tide gauge under footbridge, and thalweg elevations from PWA surveys.

Notes: Red triangles show maximum surveyed thalweg elevation for the labeled survey date

figure 4-2

Crissy Field Marsh Expansion Study

Measured Water Surface Elevations & Maximum Thalweg Elevations
November 1999 through September 2002

PWA#: 1623

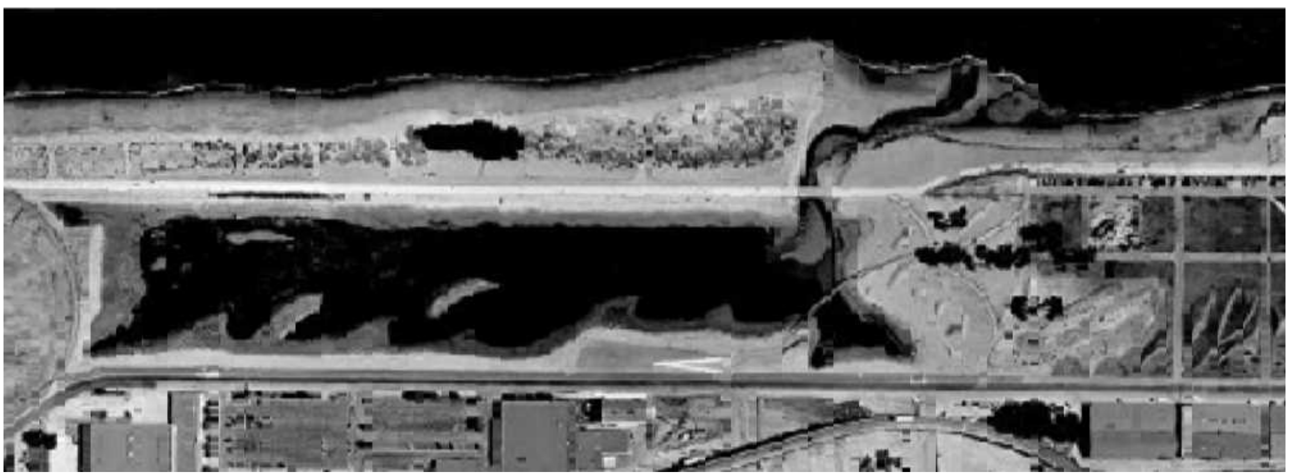
figure 4-3

Aerial Photographs Showing Inlet Evolution

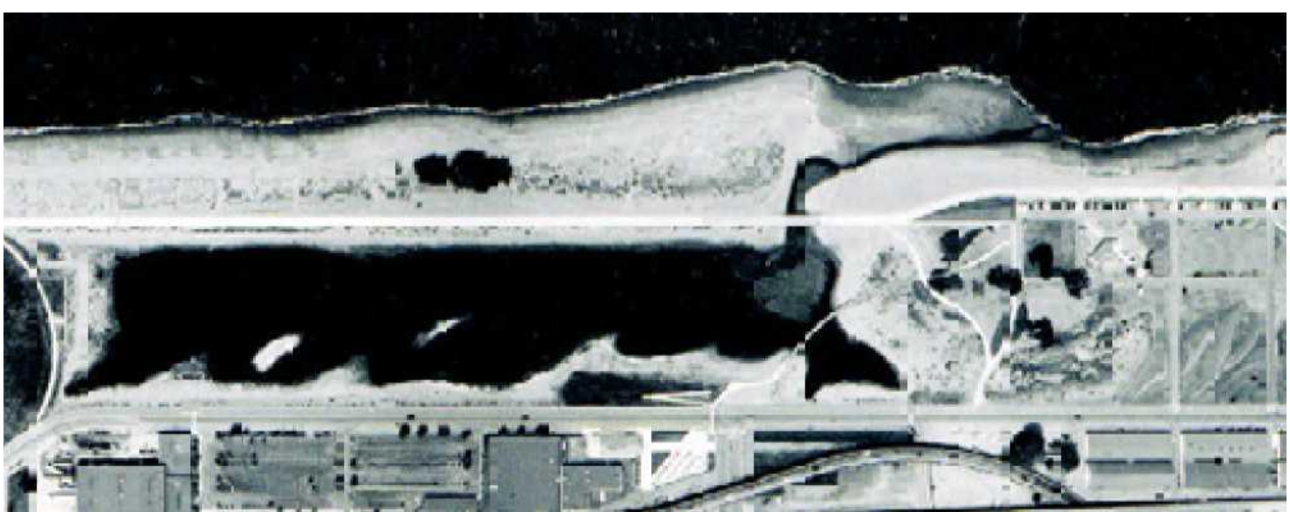
Crissy Field Marsh Expansion Study

Photographs provided by GGNRA

date of photo: 12/3/99 by Towill

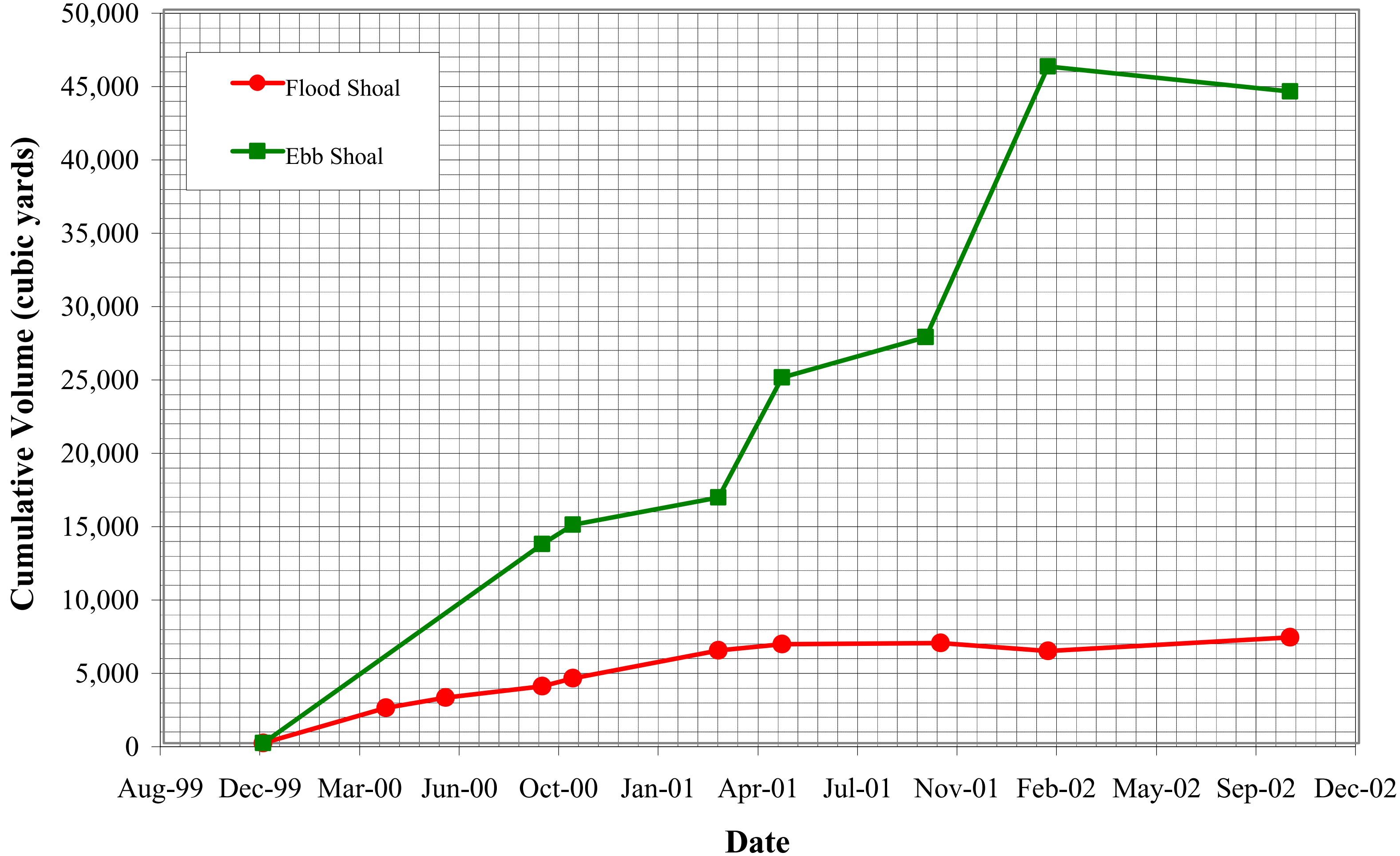


date of photo: 6/6/2000 by Towill



date of photo: 4/2/2001 by Towill

PWA



Source: PWA and Towell surveys
Notes:
- Control Volume 1 corresponds with the flood tide shoal.
- Volume change between June 1997 survey and beginning of excavation assumed to be zero.
- Volume change between breaching and December 1999 assumed to be minimal.

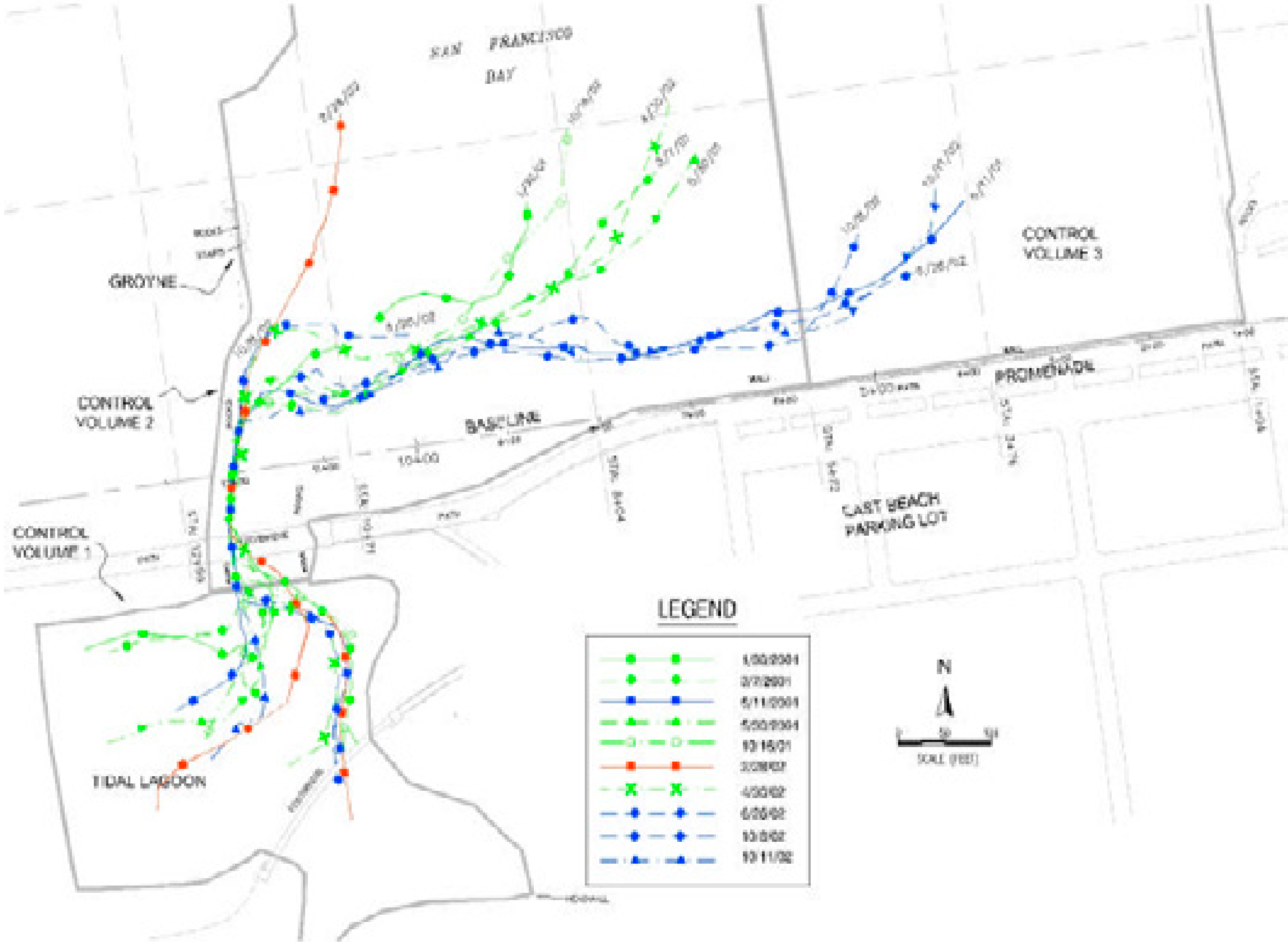
figure 4-4

Crissy Field Marsh Expansion Study

Cumulative Change in Sand Volume - Ebb & Flood Shoals

PWA#: 1623

PWA



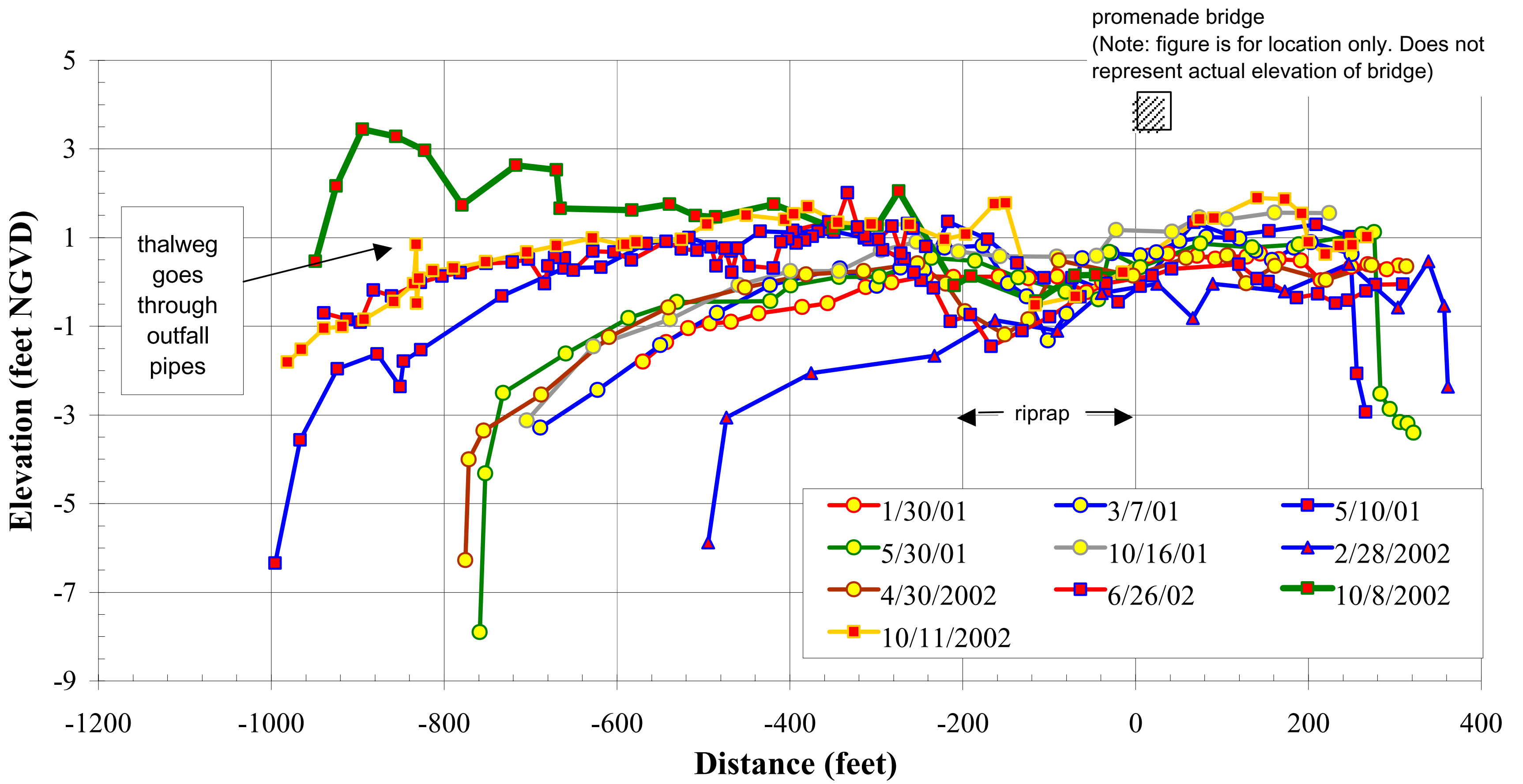
Notes: Planview of thalweg of inlet channel.
2/28/02 survey followed mechanical breach on 1/16/02.

Source: PWA and GGNRA survey

figure 4-5

Crissy Field Marsh Expansion Study
Alignment of Inlet Channel (2001-2002)

PWA#: 1623



Note: Locations of cross sections and riprap are approximate and vary depending on orientation of channel.

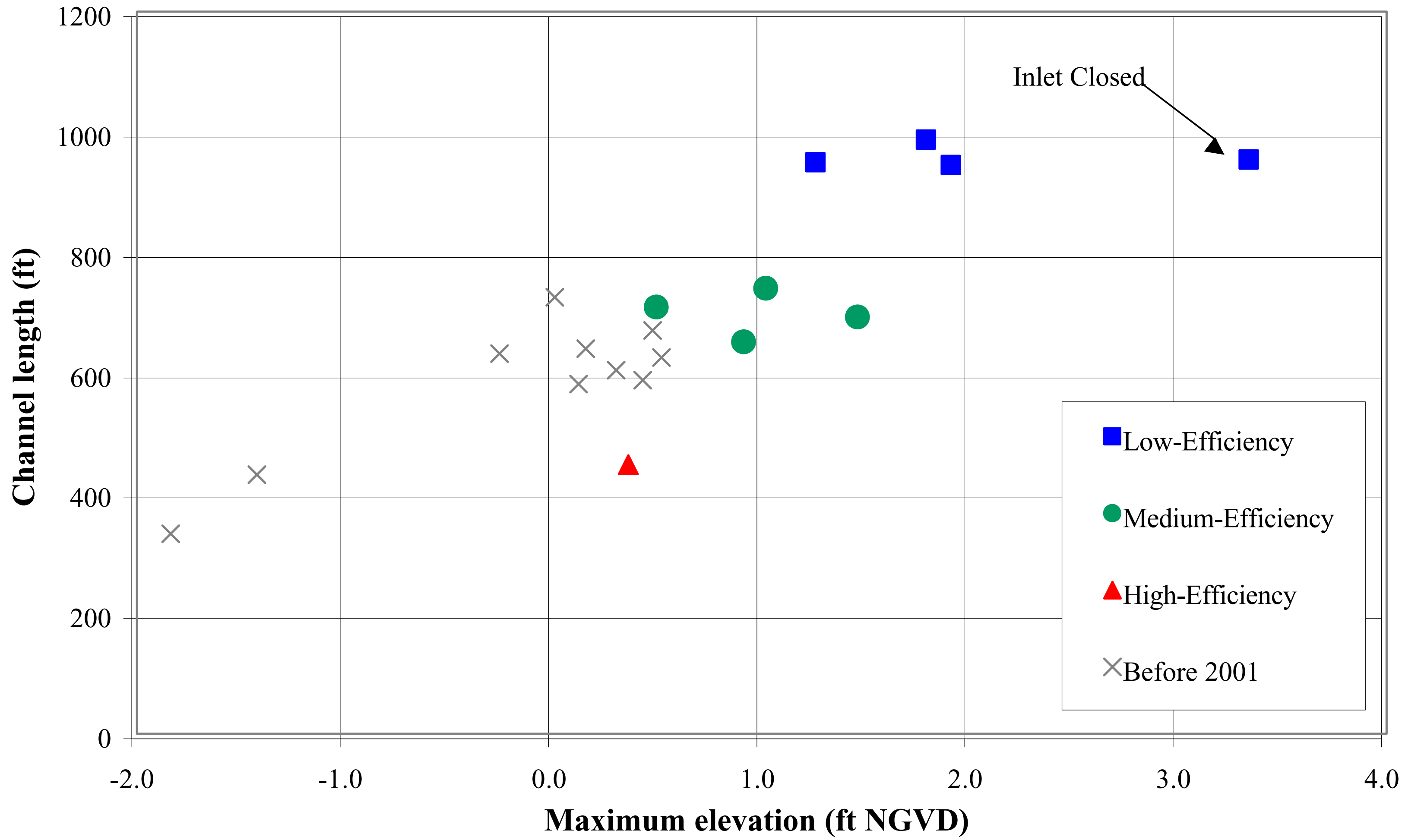
Source: PWA and GGNRA surveys.

figure 4-6

Crissy Field Marsh Expansion Study

Entrance Channel Longitudinal Profile

PWA#: 1623

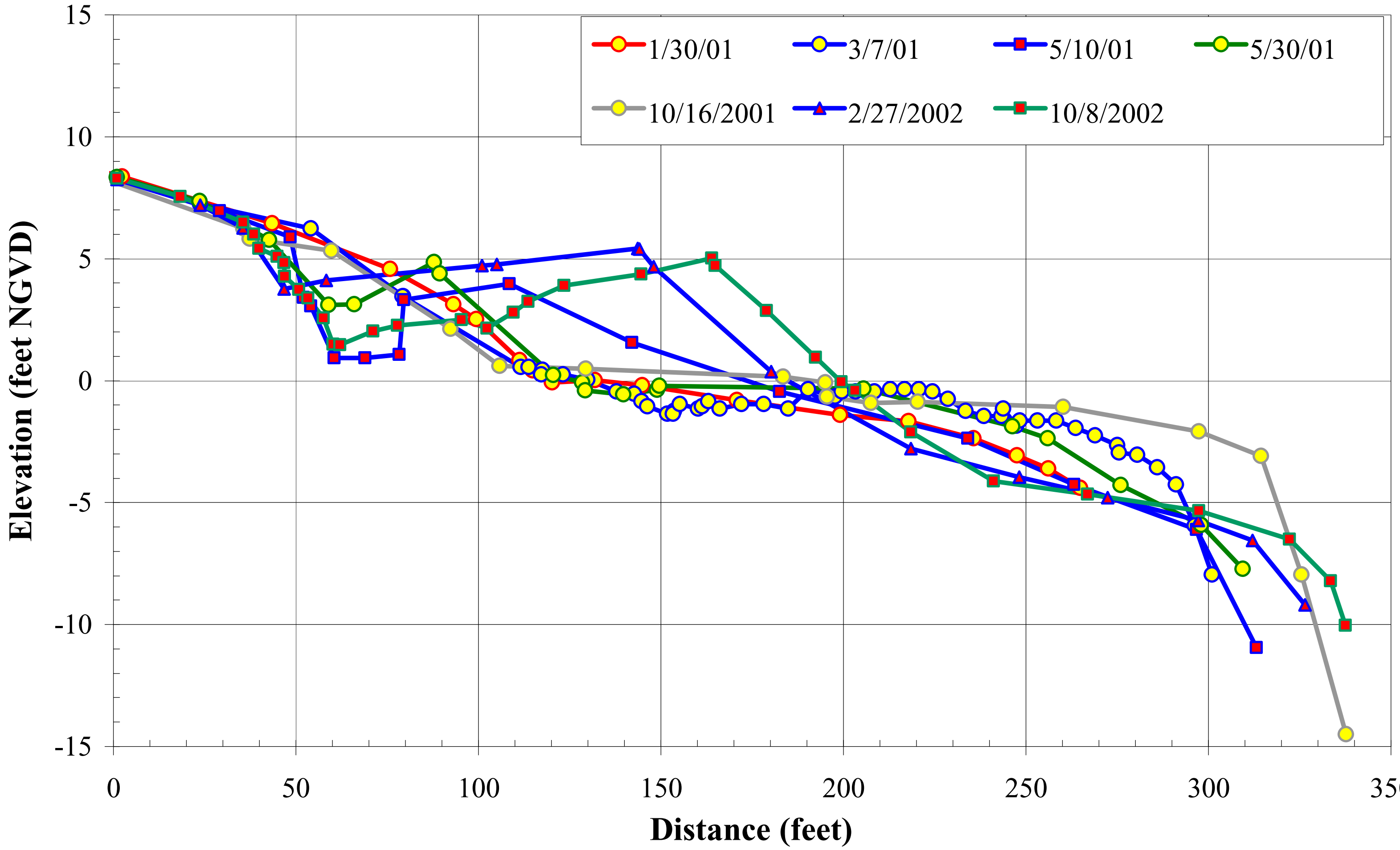


Notes
Source: PWA and GGRNA surveys.

figure 4-7

Crissy Field Marsh Expansion Study
Channel Length and Thawleg Elevation

PWA#: 1623



Notes: Profile 14E located at Staion 8+04 (see Figure 4-1 for location map).

Source: PWA surveys.

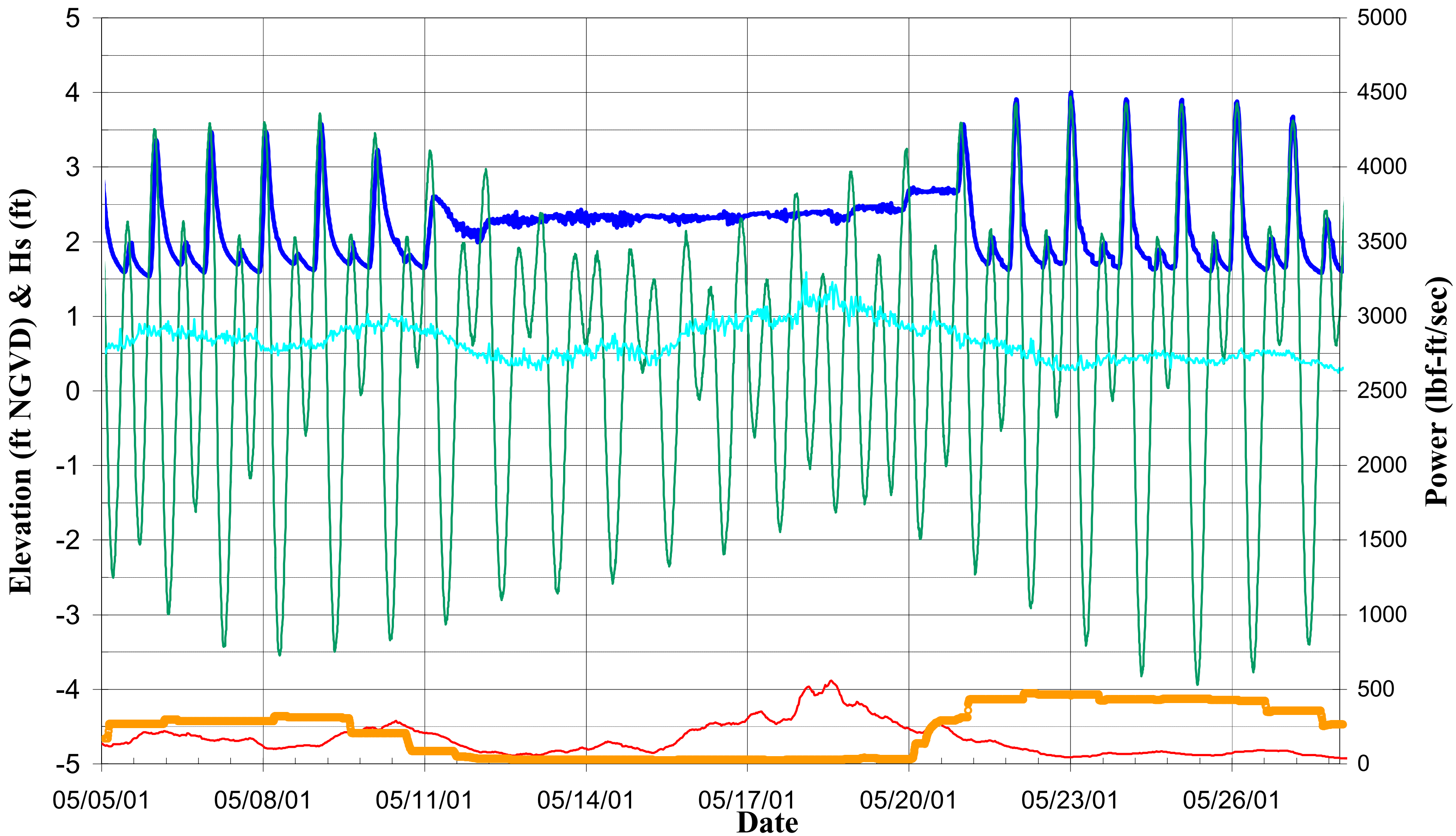
figure 4-8

Crissy Field Marsh Expansion Study

Beach Profile 14E

PWA#: 1623

PWA



Notes: Wave power is 6.25-hr moving average. Tides from NOAA (Presidio gauge), and waves from Pt Reyes Buoy (transformed).
Hs = Significant wave height

Source: PWA, CDIP, NOAA.

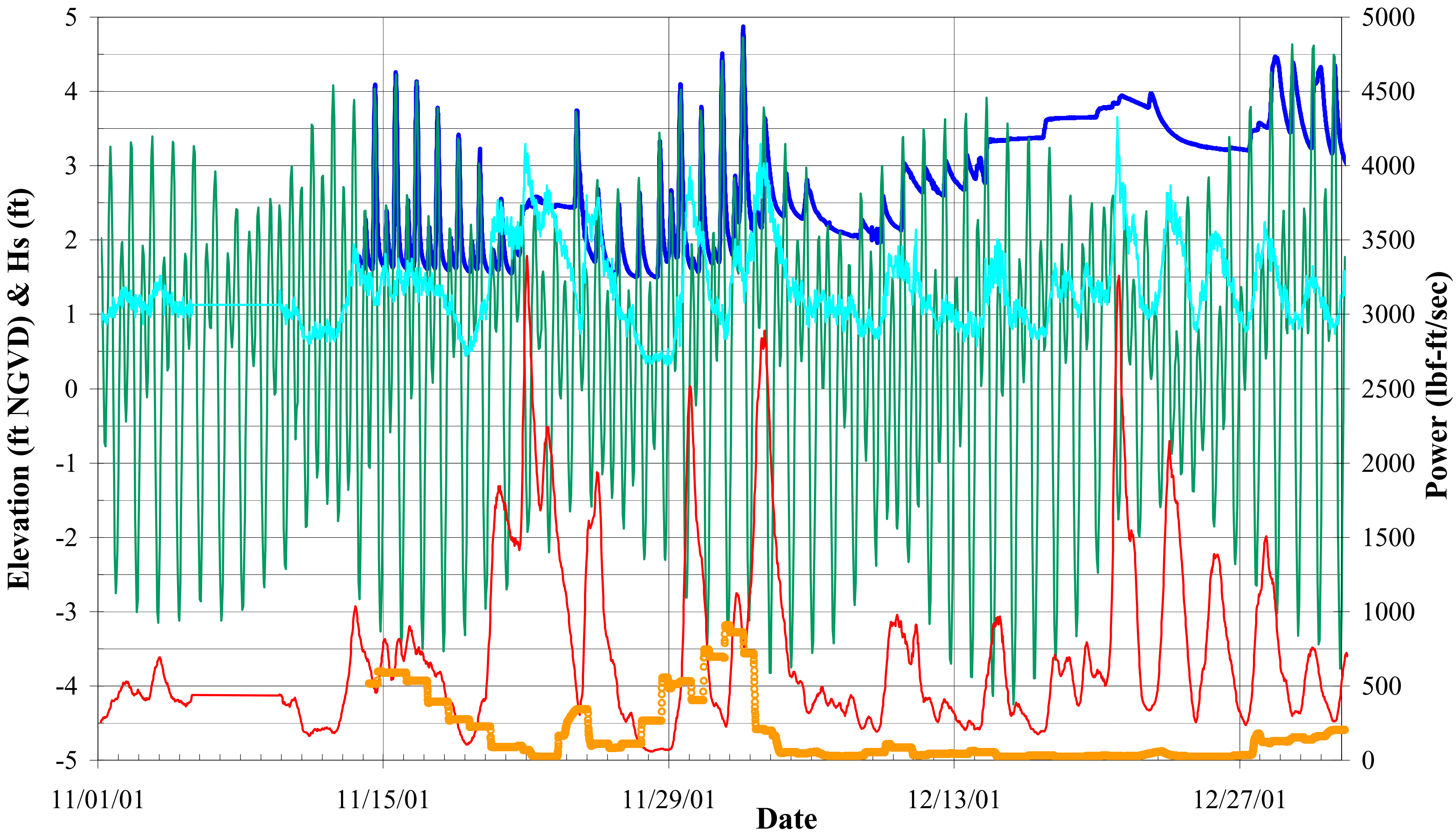
figure 4-9

Crissy Field Marsh Expansion Study

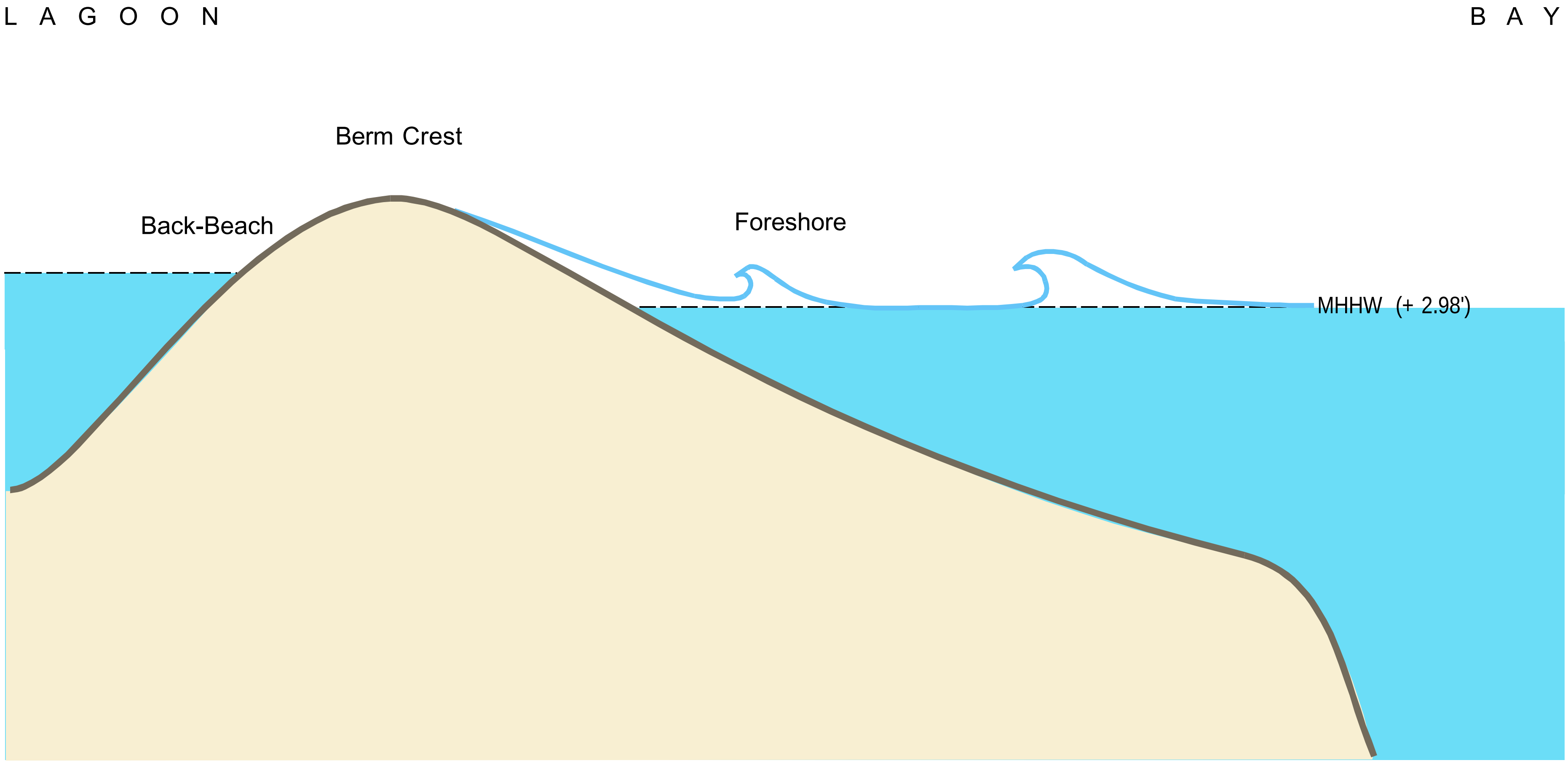
Closure Due to Small Seas

PWA#: 1623

PWA



Notes: Wave power is 6.25-hr moving average. Tides from NOS (Presidio gauge), and waves from Pt Reyes Buoy (transformed). Hs = Significant wave height Source: PWA, CDIP, NOAA/NOS.	Crissy Tides Bay Tides Crissy Hs Crissy Wave Power Tidal Power	*figure* 4-10 ***Crissy Field Marsh Expansion Study*** Closure Due to High Swell PWA#: 1623



Note: Not to Scale

figure 4-11

Crissy Field Marsh Expansion Study

Conceptualized Over-Topping During Closure

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PWA

Pre-breach inundation (14:46)

Initial ebb flow (15:43)

Continued ebb flow (15:57)

Channel scour (16:39)

Continued scour (17:10)

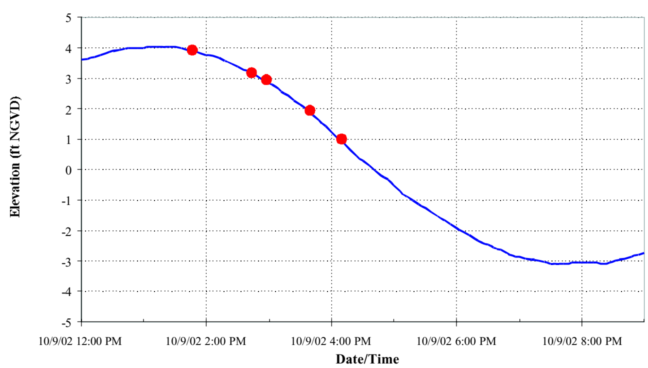


figure 4-12

Crissy Field Marsh Expansion Study

Breach of October 9, 2002

PWA

P:\Projects\1623-00_CrissyField_Expansion_Study\Task10_Reporting\Draft2_032803\OldFigs\Fig4-12.cdr

figure 4-13

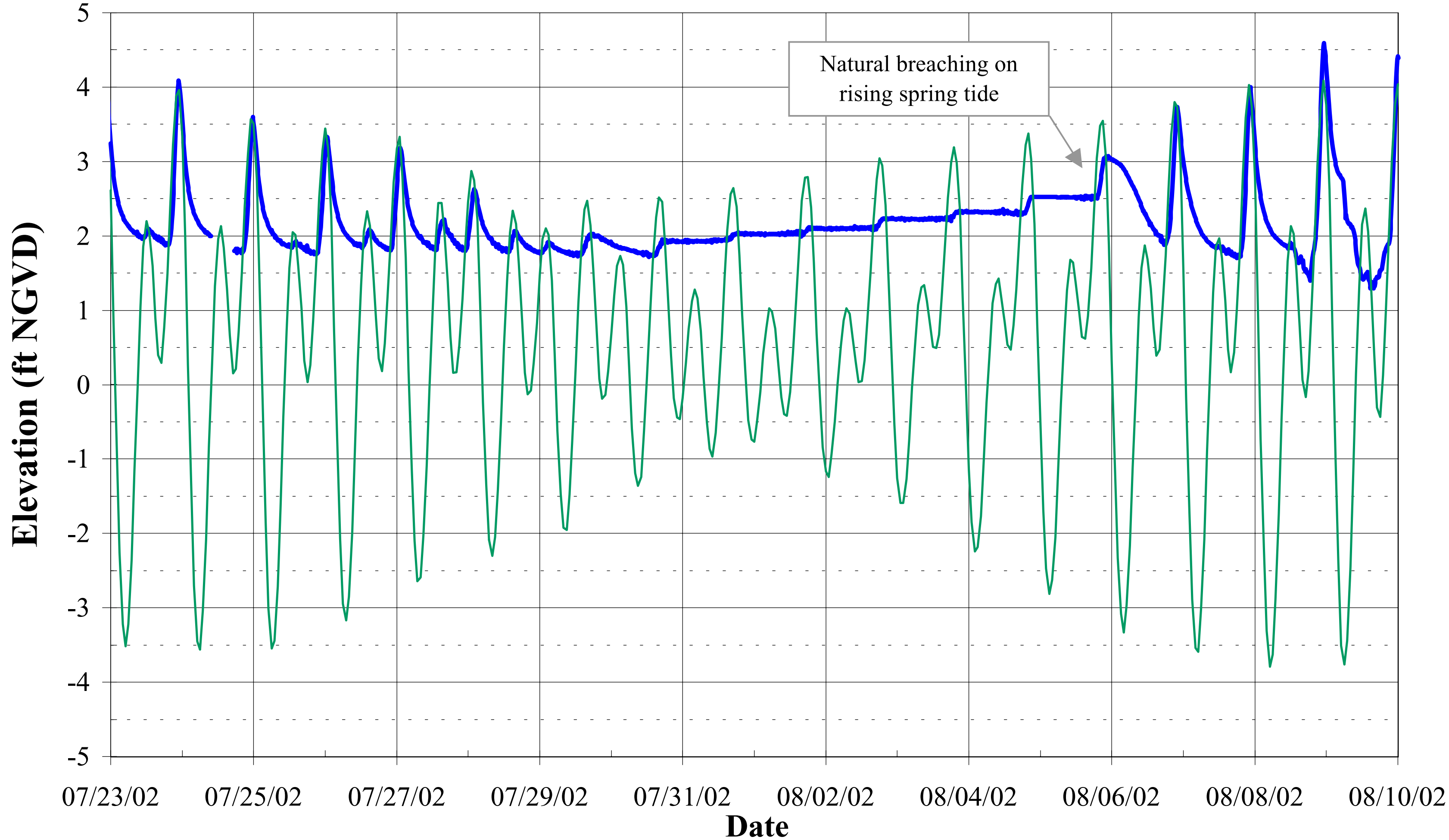
Crissy Field Marsh Expansion Study

Seepage Flow During Closure

PWA#: 1623

PWA

P:\Projects\1623-00 CrissyField Expansion Study\Task10 Reporting\Draft2 032803\OldFigs\Fig4-13.cdr



Source: Observed bay tides from NOAA/NOS station 9414290. Crissy tides from NPS.

Notes: Elevation of bay tides have been converted from MLLW to NGVD using NGS published conversion of 2.85 ft.

Crissy Tides

Bay Tides

figure 4-14

Crissy Field Marsh Expansion Study

Closure and Natural Re-Opening of August 2002

PWA#: 1623

PWA

5. THE QUANTIFIED CONCEPTUAL MODEL

The conceptual model described above 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. This Quantified Conceptual Model (QCM) is based upon a stability index to estimate the likelihood for closure and a breach criterion based upon water levels in the bay. The paragraphs below describe the details of the QCM, as well as its calibration and limitations. Conventional inlet stability criteria are also summarized.

5.1 INLET STABILITY CRITERIA

The dynamics of tidal inlets vary greatly, from sites which are continually open with relatively small changes in location and shape, to inlets that are ephemeral or subject to intermittent opening and closing. Inlet stability is primarily a function of the opposing forces of waves that move sediment into the mouth of the inlet and tidal action that scours deposited material from the channel, and stability criteria that directly or indirectly incorporate these processes. Stream discharge can significantly augment or replace tidal power as the scouring force, but creek flow into Crissy Field from Tennessee Hollow is relatively weak and therefore neglected in the following discussion. Proposed stream restoration activities in the Tennessee Hollow watershed should not significantly change this.

The paragraphs below summarize criteria that have been used by others to determine the stability of tidal inlets. Along with the summary of each criteria, its applicability to the present study is qualitatively addressed.

5.1.1 Tidal Prism Relationships

Hydraulic geometry relationships between tidal prism and the cross-sectional area of the inlet channel are perhaps the most common criteria applied to predict the stability of tidal inlets. These are empirical relationships based on surveys of stable inlets, and take the form:

$$A_e = C\ \Sigma^n$$

where A_e is the minimum cross-sectional area, Σ is the tidal prism, and C and n are empirically derived parameters. Jarrett (1976) examined earlier work by O'Brien (1931) for Pacific Coast inlets, and established relationships for sites along the Gulf and Atlantic coasts. His results were further divided among inlets that had one, two, or no jetties. Although the expressions established by Jarrett are considered the best available predictors for equilibrium cross-sectional areas, small inlets tend to exhibit equilibrium area much larger than predicted by these tidal prism relationships.

Considerable scatter in the data suggest that not all of the relevant processes are included in these simple relationships. Therefore, they should only be used as a first approximation and interpreted as representative of long-term average conditions. Significant variations can occur over the spring-neap tide cycle, during storms when wave attack is more intense, or following large flood events. This is especially true for small dynamic systems such as the Crissy Field inlet. A process-based tidal prism relationship developed by Hughes (2002) shows better agreement between small and large tidal inlets, and more promise for application to the Crissy Field inlet.

5.1.2 Wave Power versus Tidal Prism

Tidal inlets reach an equilibrium configuration when the sediment 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, O'Brien (1971) proposed the following closure criteria:

$$S = P_W/P_{T,}$$

where, P_W is the wave power and P_T is the tidal power per tidal cycle. O'Brien postulated that the inlet would close if the stability parameter, S, exceeded some critical value, S_{CRIT}.

Although tidal currents complicate the movement of sand, O'Brien speculated that wave power could still be used as a reasonable surrogate for littoral transport. It was also noted that not all of the tidal energy is available for maintenance of the flow area since some is dissipated by friction along the channel and head losses in the ocean (bay) and basin (lagoon).

Despite its limitations, the O'Brien stability criterion explicitly accounts for the opposing forces of waves and tides and is capable of predicting stability over the short-term due to time-varying conditions. Therefore, it can be used to simulate discrete inlet closure events based on a time series of wave and tide data. Application to the present study relies upon selection of S_{CRIT} and the availability of input data.

5.1.3 Johnson's Wave Power – Tidal Prism Criterion

Johnson (1973) noted that nearshore wave data needed to apply O'Brien's closure criterion 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.

After graphically presenting his results, Johnson identified a line that separates inlets that have closed or are usually closed and those that stay open. Like the tidal prism relationships, this criterion gives a general indication of the long-term stability of the inlet, but cannot provide more than a qualitative indication of the frequency of closure. PWA (1999) noted corrections to the data from Johnson (1973) that affect the wave power values reported but not the validity of the approach.

5.1.4 Littoral Drift versus Tidal Prism

Bruun (1966, 1978) examined the delivery of sediments into the mouth of the inlet by littoral transport and compared this to the neap tidal prism. From these studies, he developed stability criteria based on total annual littoral drift (M) and neap tidal prism (Σ_N). The stability of an inlet is rated as good, fair or poor according to the ratios:

$\Sigma_N / M > 150$	good
$100 > \Sigma_N / M < 150$	fair
$50 > \Sigma_N / M < 100$	fair to poor
$\Sigma_N / M < 50$	poor

Longshore transport during storms is assumed to contribute most of the sediment, however cross-shore transport may be significant under certain conditions. The usefulness of the Bruun stability criteria is limited by the ability to accurately predict the longshore transport.

5.1.5 Peak Tidal Current

Escoffier (1940) proposed a semi-analytic method for developing stability criteria based on the peak tidal velocity (U_{MAX}) and the cross-sectional area (A_C). Peak velocities are based on numerical models or analytic methods. Escoffier curves (U_{MAX} versus A_C) suggest three possible scenarios:

1. *Inlet normally closed*. If U_{MAX} is less than the velocity required to remove sediment from the previous tidal cycle (U_{CRIT}) the inlet will close.
2. *Unstable Inlet*. If U_{CRIT} intersects the curve, there are two possible solutions. The first solution (the lower value of A_C) is unstable since initial change in flow area is accentuated and the inlet will continuously shoal until closure or, scour until critical flow area is attained.
3. *Stable Inlet*. The second intersect of U_{MAX} and U_{CRIT} (the larger value of A_C) indicates a stable inlet since any induced changes in the cross-sectional area of a stable inlet will result in a change of velocity that returns the inlet to its original size by deposition or scour.

Implicit in this analysis is that the inlet dimensions will change in time, in response to the spring neap cycle as well as seasonal and other trends in the forcing parameters. Seasonal changes are associated with storms and are characterized by changes in cross-sectional area about an average value. It should also be noted that even stable inlets may be subject to perturbations under extreme conditions that result in the inlet area changing to unstable values. The joint probability of these conditions (high wave, tides, and freshwater runoff) affects the expected frequency of closure.

5.2 DETAILS OF THE QCM

The conceptual model described in Section 4.2 was extended to a computer program that uses time series of wave and tidal levels to estimate the potential for inlet closure and breaching at Crissy Field. The output of this FORTRAN program is a corresponding time series of a stability parameter, with a time history of closure and breach events. The QCM uses a modified O'Brien stability criterion to quantify the time-varying potential for closure (Williams and Cuffe, 1994; PWA, 1993) and a simple breach criterion based upon the elevation of tides in the bay and the beach barrier.

5.2.1 Closure Potential

Closure potential is estimated by applying a time-varying O'Brien stability index based on the changing environmental conditions at Crissy Field. This stability index is simply the ratio of wave to tidal power, and can be defined as:

$$S = P_W/P_T$$

where, P_W is a moving 6.5-hour average of the wave power at Crissy Field, and P_T is the tidal power of the marsh. The inlet will close if the stability index exceeds some critical value (S_{CRIT}).

Wave power is the rate of energy flux, and is defined as:

$$P_W = \frac{1}{2} \Delta g H^2 Cg$$

In this expression, Δ is the density of seawater, H is the wave height at Crissy Field, Cg is the group velocity (i.e., the speed at which wave energy travels). Since the group velocity depends on the wave frequency, contributions from individual wavelets must be computed separately and then summed to provide the total wave power. Therefore,

$$P_W = \frac{1}{2} \Delta g \Sigma_i H_i^2 Cg_i$$

where the subscript *i* represents various frequency bands in the wave spectrum. This expression can be similarly extended to sum contributions from different wave directions. In the present application, directionality is implicitly included in the wave transformation matrix.

Tidal power represents the rate at which the potential energy of the water flushed through the inlet is spent, and is defined as:

$$P_T = (\gamma \Omega R) / (b T)$$

where, γ is the unit weight of water, Ω is the effective diurnal tidal prism, R is the effective diurnal tide range in the lagoon, b is the width of the inlet, and T is the period over which the water level in the lagoon varies. It is important to note that in its present morphological condition, the effective tidal prism at Crissy Field is significantly less than its potential tidal prism. As discussed in Section 4.1 is due to the relatively high elevation of the inlet channel thalweg which limits tide range in the lagoon. Due to this tidal muting, the expected tide range in the lagoon is determined by the higher high (HH) water level in the bay and the low water (LW) elevation set by the maximum thalweg elevation. Since the majority of the effective tidal prism is drained during the first ebb cycle in the bay, tidal power at Crissy Field is computed by setting T to 6.25 hours and taking the difference between HH and LW as the effective tidal range in the marsh. This formulation remains applicable as the effective tidal range increases to a larger percentage of the potential (bay) tide range.

Using input time series of wave and tide data, and setting the low water drainage elevation based on monitoring data, a time-varying stability index was computed. An example of this is shown in Figure 5–1, which plots the wave and tidal conditions as well as stability index computed by the QCM for the period of 06/04/2001 to 06/20/01. According to the O'Brien criterion, closure occurs when the stability index exceeds some critical value, S_{CRIT}.

5.2.2 Breaching

As described in Section 4.2, natural re-opening of the tidal inlet at Crissy Field is usually driven by the difference in elevation between the high tides in the bay and the beach barrier. Therefore, the following criterion was used to determine if a closed inlet would naturally re-open,

if $\eta_{BAY} > \eta_{CRIT}$, the inlet naturally breaches
if $\eta_{BAY} < \eta_{CRIT}$, the inlet stays closed

where, η_{BAY} is the observed water level in the bay and therefore includes the meteorological and hydrological effects as well as the tides. η_{CRIT} is the critical value the bay water level must exceed in order to breach the beach barrier. Observations of natural breaching events indicate that the closed inlet tends to re-open near the remnant mouth, where the crest of the barrier is minimum. Since closure occurs when sedimentation near the mouth creates a barrier sufficient to block tidal inundation during flood currents, η_{CRIT} is initially set slightly higher than the coincident high tide in the bay. This value is subsequently increased as a function of wave power incident on the closed inlet to account for beach processes that tend to increase the beach berm elevation. The critical bay water level required to induce natural re-opening, therefore, is modeled in the QCM with the following expression,

$$\eta_{CRIT} = [HW_O + a] + [b \times \int P_W \, dt] + [\Sigma \, (c \times P_{W\text{-}Peak})].$$

HW_O is the diurnal high tide in the bay at the time of closure, $P_{W\text{-}Peak}$ is the peak incident wave power above a critical value, t is time since closure, and a, b, and c are calibration coefficients. The first term in brackets represent the initial elevation of the beach berm immediately following closure. The second and third terms represent increases in the berm elevation due to, respectively, the cumulative and peak wave power incident upon the beach during closure. Based on survey data η_{CRIT} is limited to 5 ft NGVD, the highest expected elevation of the beach barrier. This elevation relates to the typical beach morphology at Crissy Field, as defined by wave run-up at high tides.

Since water levels in the bay may not reach the critical elevation required to naturally re-open a closed inlet if the beach barrier is sufficiently large, the QCM assumes that intervention (mechanical breaching) will take place once the duration of closure reaches 14 days. This ensures at least one spring tide cycle has passed without bay tides high enough to naturally re-open the inlet.

5.2.3 Channel Alignment

As described in Section 4.1, the inlet channel responds to changing wave conditions by migrating between one of two natural positions, which in turn affects the low water drainage elevation. The low water drainage elevation is an important parameter and strongly affects tidal power and hence the stability index. Since wave conditions along California generally exhibit the seasonality of strong winter storms and relatively low-energy summer waves, the low water drainage elevation is prescribed in the QCM based on the calendar month.

After examining the monitoring data shown in Figure 4-2, the following values were selected for low water drainage elevations in the marsh. Note that the low water elevation is slightly higher than the maximum thalweg elevation due to frictional losses along the channel length.

LW = + 1.75 ft NGVD	From June to September
LW = +1.50 ft NGVD	October to April
LW varies from +1.75 to +1.5 ft NGVD	October
LW varies from +1.5 to +1.75 ft NGVD	May

Low water elevations in the marsh are lower following mechanical breaching, and persist for several months. Following the mechanical intervention of mid-January 2002 the low water dropped from its initial elevation of +1.5 ft NGVD to approximately +0.3 ft NGVD by mid-to-late March 2002 as the inlet channel slowly downcut. Sedimentation in the channel then returned, and by mid-June 2002 the low water elevation was again +1.5 ft NGVD.

5.3 INPUT DATA

Time series of tide and wave data were collected from readily available sources and used as input to the QCM. Historical tide data were collected from verified water surface elevations observed at the Presidio tide gage[1]. The daily high and low water surface elevations and times of these events were used to compute the tidal power at the Crissy Field marsh. Samples of these data are shown in Table 5-1.

[1] NOAA station 9414290. Data available from http://www.co-ops.nos.noaa.gov

Table 5-1. Sample Tide Data from Presidio Gage

```
Data are in Feet above MLLW
Times are on UTC (GMT)
9414290 SAN FRANCISCO, SAN FRANCISCO BAY, CA  from  20011201 to 20021101
Click HERE for further station information.
--------------------------------------------------------------------------------
Station Date       Time      WL  TY

9414290 2001/12/01 01:18   -0.67 LL
9414290 2001/12/01 08:30    4.98 H
9414290 2001/12/01 12:42    3.16 L
9414290 2001/12/01 18:54    7.25 HH
9414290 2001/12/02 01:54   -0.55 LL
9414290 2001/12/02 09:18    5.61 H
9414290 2001/12/02 13:42    4.31 L
9414290 2001/12/02 19:36    7.62 HH
9414290 2001/12/03 02:48   -0.33 LL
```

Offshore wave data collected by the California Data Information Program (CDIP) of the Scripps Institute of Oceanography were transformed to construct a time series of nearshore wave conditions at Crissy Field using methods established by PWA as part of previous studies (PWA, 2001a). CDIP collects directional wave data from its buoy located approximately 21 miles offshore of Point Reyes[2] (see Figure 5–2 for a location map). Due to the limitations of saving and transmitting time-varying directional wave spectra, data from this buoy are summarized into nine period bands. Each band contains the energy content for a range of wave frequencies and is assigned a dominant wave direction. Tables 5-2 and 5-3 show sample data from the Pt. Reyes buoy, and illustrate how the energy content and directionality of each period band is summarized from offshore measurements.

Table 5-2. Sample Directional Data from CDIP Buoy

ANGULAR DISTRIBUTION IN PERIOD BANDS (ANGLES IN DEGREES)										
UTC	Dp	BAND PERIOD LIMITS (SECS)								
YYYYMMDDHHMM	(DEG)	+22	22-18	18-16	16-14	14-12	12-10	10-8	8-6	6-2
199612060136	304	302	306	309	303	303	304	293	283	265
199612060206	302	304	308	310	303	306	302	294	283	265
199612060236	306	314	306	308	309	311	305	299	286	264
199612060306	310	317	308	309	309	309	310	298	285	262

[2] CDIP Pt. Reyes Buoy (station ID 029). Data available from www.cdip.ucsd.edu

Table 5-3. Sample Wave Energy Data from CDIP Buoy

						ENERGY (CM^2)						
UTC	Hs	Tp				BAND PERIOD LIMITS (SECS)						
YYYYMMDDHHMM	(CM)	(SEC)	+22	22-18	18-16	16-14	14-12	12-10	10-8	8-6	6-2
199612060136	389	11	196	2064	417	574	1072	2190	1382	800	725
199612060206	382	11	274	1261	449	493	1244	2661	1283	827	658
199612060236	413	20	155	2918	1353	467	1415	1950	933	952	533
199612060306	408	11	196	1754	1028	689	1931	2230	1246	714	607

Offshore wave energy was transferred to nearshore values based on methods established in previous studies (PWA, 2001a). The approach uses a transformation matrix derived by comparing directional wave data measured offshore at Point Reyes and at Crissy Field, about 300 yards to the east of the inlet and in a water depth of 10 meters. Coefficients from the transformation matrix are used to estimate nearshore wave heights from offshore conditions. Implicit in this analysis is the assumption of 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 (2001a).

5.4 CALIBRATING THE QCM

Calibration of the QCM program consisted of selecting the critical values for closure (S_{CRIT}) and breaching ($>_{CRIT}$), and comparison of predicted closure and breaching events to those observed and listed in Table 4-2. Although instrument malfunction and maintenance prohibited a continuous record of water levels, the available data show several closure and breaching events since May 2001. Due to the strong influence of mechanical breach on January 16, 2002 on the hydraulics of the inlet, this event was hard-wired into the QCM program for calibration purposes. This assured that the model reflected the subsequent increase in tidal power due to improved low water, and that it would not predict closure events that might have otherwise occurred immediately following the intervention.

Examination of the stability index during these observed closure events reveals a minimum critical value of approximately 12. An example of this calibration data is shown in Figure 5–3, which plots the measured water levels and estimated wave and tidal power at Crissy Field for the period of 4/21/2001 to 6/15/2001 and included two closures and breach events. Note that during the closure of 5/12/2001 the effective tidal power in the marsh is reduced not just by the low water drainage elevation, but also by incomplete filling during the flood cycle. Variability in tidal power is more typically associated with the spring neap cycle and storm surges generated by low-pressure systems that pass the San Francisco Bay Area. The observed high tides recorded by the Presidio gage include both of these astronomical and meteorological effects, and can be used with reasonable confidence as a surrogate for high water levels in the lagoon.

The QCM was calibrated by simulating the stability index for the period from January 2001 through November 2002, and adjusting the values for closure (S_{CRIT}) and calibration parameters determining natural breaching ($>_{CRIT}$). Time series of the stability index, tides, and significant wave height for the period of 4/21/2001 to 6/15/2001 are plotted in Figure 5–4. Most of the intermittent closures and natural re-opening events over the entire calibration period are captured by the calibrated QCM, as summarized in Table 5-4. The QCM did less well at predicting the details of the closures from November 2001 through January 2002, when a series of large wave events dramatically affected the hydraulic efficiency of the inlet, and ultimately lead to the unplanned mechanical breach on January 16, 2002 by non-NPS staff. However, the model did predict a series of closure events (simulated closures #5 through #7) in response to these winter storms, with one event requiring intervention (simulated closure #7).

Table 5-4. Simulated Closure Events During Calibration Period

Closure	Dates		Days	Index	Wave Power	Tidal Power	HH-1	HH-2	Berm	Breach
1	4/30/2001	5/5/2001	5.2	12.7	482.6	38.1	2.00	3.46	3.35	Nat
2	5/15/2001	5/20/2001	4.9	12.4	72.3	5.8	1.99	3.53	3.30	Nat
3	6/13/2001	6/18/2001	5.1	45.6	179.0	3.9	2.13	3.54	3.39	Nat
4	10/24/2001	11/5/2001	11.9	46.7	333.2	7.1	1.98	3.27	3.56	no data
5	11/20/2001	12/1/2001	11.4	29.5	1596.3	54.1	2.34	4.77	4.65	Nat
6	12/6/2001	12/9/2001	2.7	14.2	367.8	25.9	2.12	3.40	3.37	Nat
7	12/20/2001	1/3/2002	14.0	12.2	737.0	60.5	2.67	3.09	5.32	Mech
8	6/1/2002	6/10/2002	9.1	12.5	801.5	64.2	2.14	3.75	3.69	Nat
9	6/30/2002	7/8/2002	8.9	50.8	274.9	5.4	2.14	3.61	3.47	Nat
10	8/26/2002	9/3/2002	7.3	18.9	124.7	6.6	2.16	3.50	3.44	Nat

Wave Power = Estimated wave power at Crissy Field at time of closure [lbf-ft/sec].
Tidal Power = Tidal power at time of closure [lbf-ft/sec].
HH-1 and HH-2 = Observed diurnal high water in bay day of closure and breach, respectively [ft NGVD].
Berm = Estimated berm elevation [ft NGVD].
Breach = Natural (Nat) or mechanical (Mech) breach. No data = data gap during closure, therefore inlet reset to open.

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. Figure 5–5 plots the bay tides, wave power at Crissy Field, and the simulated berm elevation during closure events #5 through #7. Calibration of $>_{CRIT}$ produced a berm elevation that allowed for natural re-opening of closures #5 and #6, but mechanical intervention of closure #7. This is generally consistent observation shown in Figure 4–9. Monitoring data from the marsh tide gage reveal that the inlet was significantly restricted (low water drainage to only +3.0 ft NGVD) before the inlet was completely blocked by a high and wide barrier (marsh water level constant at +4.0 ft NGVD) by mid-January 2003. This general, but not precise, agreement between predicted and observed closures should not be surprising given the simplicity of the QCM and complexity of the natural system.

5.5 LIMITATIONS

Although the QCM predicts the frequency of closure and natural re-opening to the level of accuracy appropriate for a management tool, uncertainties associated with its simplified structure and the variability of the natural system should be considered when interpreting the results. The model is reasonably successful at simulating the intermittent closures at Crissy Field since the joint probability of high wave power and low tidal power can be well predicted from the observed data, and a calibrated value of the stability index has been determined. The utility of the QCM is enhanced by its simplicity – only the bay tide and offshore wave data are needed as input for a given lagoon size (effective tidal prism and range). However, uncertainties remain and include:

1. Directionality of the Offshore Wave Spectra
   Directional wave data collected at the Point Reyes buoy is condensed in order to minimize the load in storing and transmitting the information to shore. Therefore, the directionality of the offshore waves are condensed by assigning one predominant direction to each of the nine period bands. Actual wave conditions along the California coast typically include multiple wave trains that are more accurately represented by directional wave spectra, and the wave transformation coefficients used in the present study could be improved by using the full directional spectra. Such a description of wave data is available in the F291 format of data collected by the National Oceanographic Data Center (NODC), but not for the CDIP buoy at Point Reyes.

2. Limited Frequency Content of Offshore Waves
   The nine period bands used to summarize the offshore wave energy impose a fixed discretization on the wave data. Better resolution of the distribution of wave energy across the frequency spectrum could be achieved with more bands (not equally spaced) or other methods could be used to more accurately summarize the true frequency content of the sea.

3. Linear Wave Transfer Matrix
   The wave transformation matrix developed previously (PWA, 2001) and used in the present study does not account for wave breaking over the San Francisco Bar, although this occurs during high storm events, including a dependence on the magnitude of the wave heights, which is not accounted for in this approach.

4. No Wind-Wave Generation over San Francisco Bay
   Since the nearshore waves are derived by transforming wave data collected offshore of Point Reyes, local seas (waves generated by wind blowing over the bay) are not accounted for in the present method.

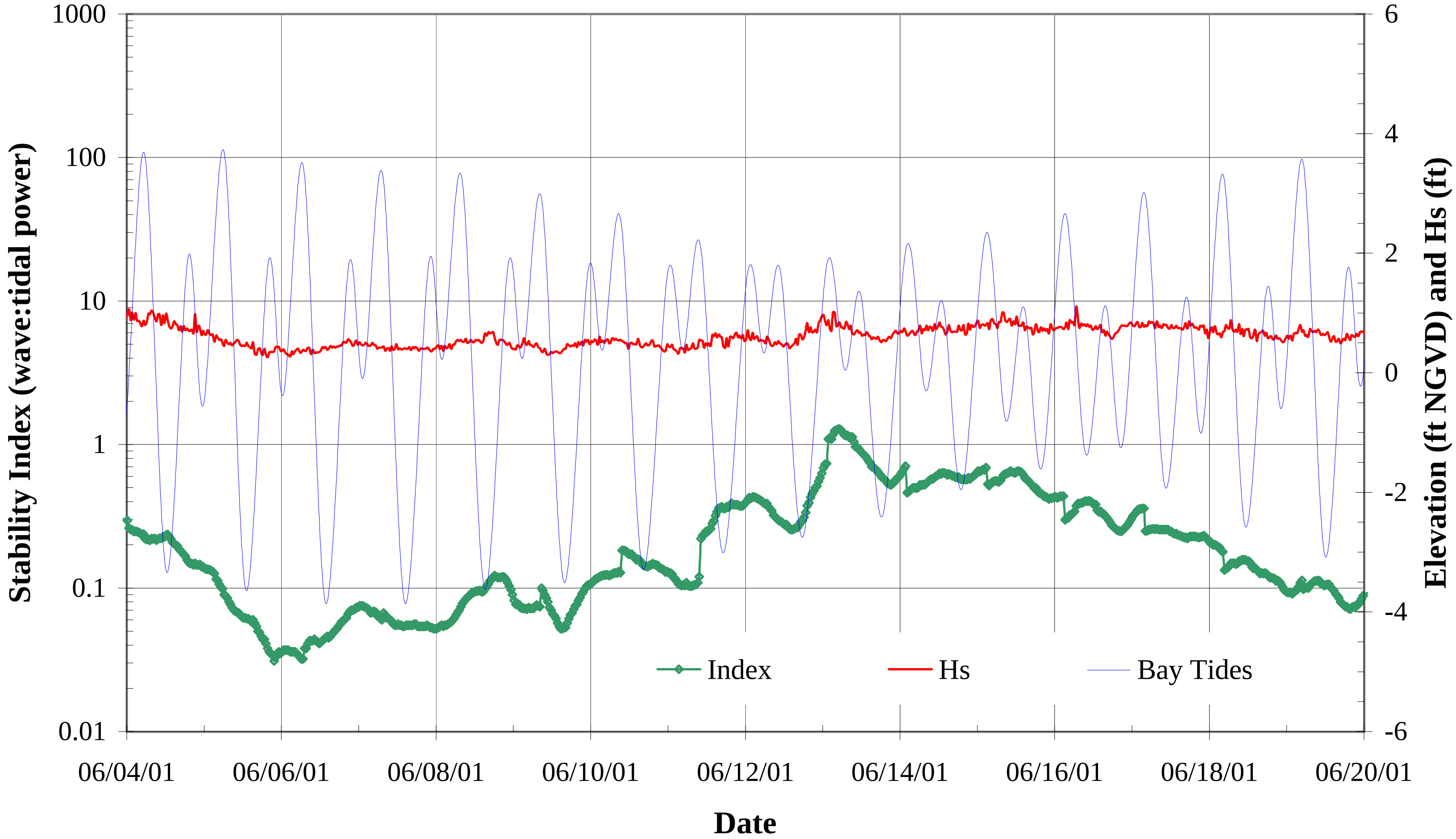
5. Wind Driven Transport not Explicitly Accounted for in QCM
   Wave power has been used as a surrogate for total sand transport into the inlet channel and onto the beach barrier, and wind driven processes have been neglected in the QCM. However, the strong and steady winds at Crissy Field also drive sediment to the east.

This Aeolian transport is probably more important in building the expansive beach barrier during periods of prolonged closure.

6. Partial Closure

   The effective tidal prism is computed assuming the lagoon high tides match the high water levels in the bay, although reduced conveyance of a partially-closed inlet may mute the high tide. Typically, high tides in the lagoon match bay levels, but in some cases strong wave action deposit enough sand in the entrance channel to preclude complete filling of the lagoon during the flood tide.

The QCM could be improved by including one or more of the above processes. However, the results obtained with the presently calibrated model appear adequate for planning purposes without these refinements.



Source: Tides from NOAA Presidio Gauge. Significant wave height (Hs) at Crissy Field from transformed

Notes:
Tide, wave, and stability index for exisiting conditions.

figure *5-1*

Crissy Field Marsh Expansion Study

Representitive Output from QCM

PWA #:1623

PWA

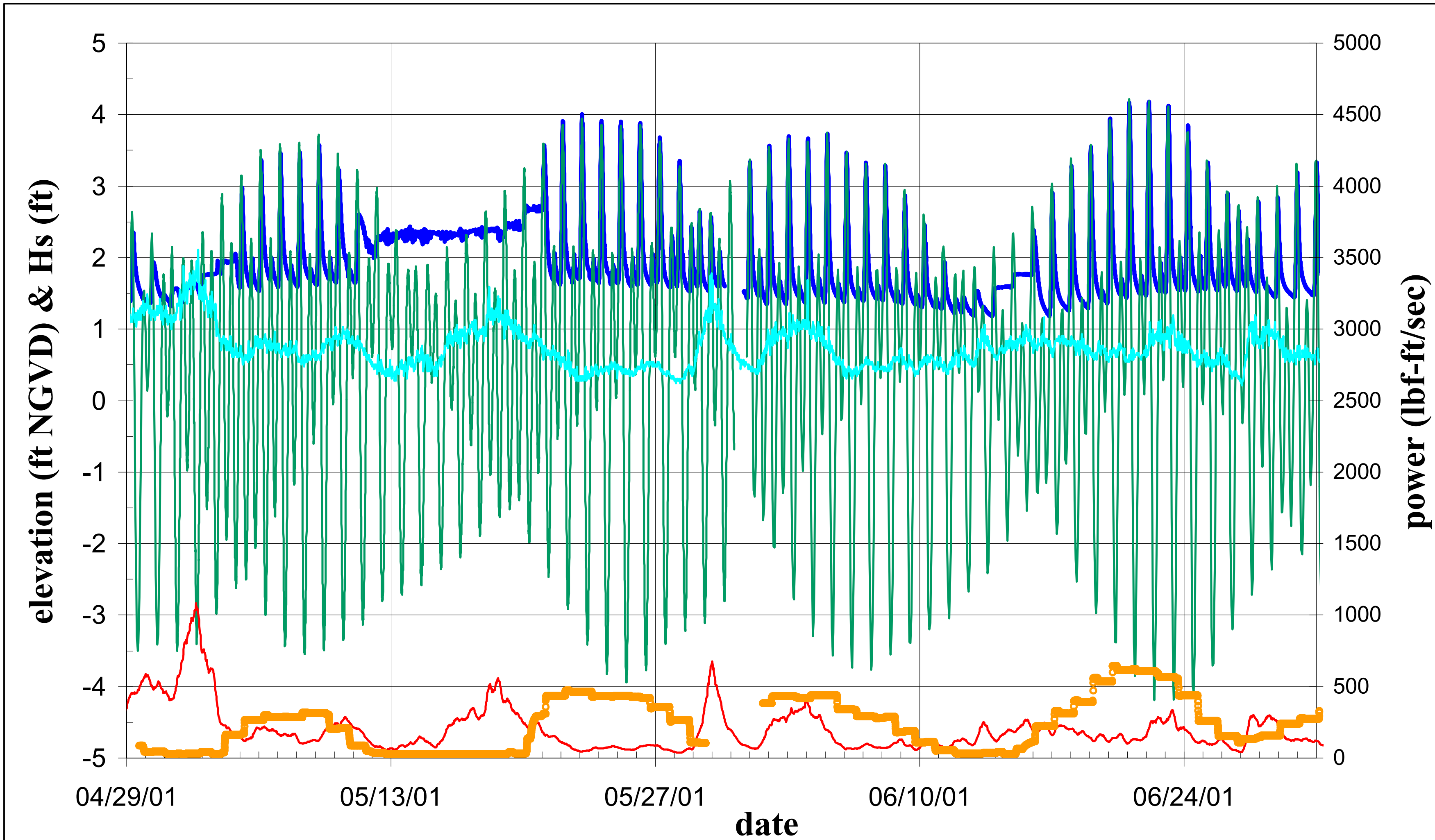
figure 5-2

Crissy Field Marsh Expansion Study

Tide & Wave Gage Locations

PWA#: 1623 PWA

Projects\1623-00_CrissyField_Expansion_Study\Task10_Reporting\Figs\Sec5\ Fig5-x_TdeWveGageLoc.cdr



Notes: Wave power is 6.25-hr moving average.
Tides from NOAA (Presidio gauge), and waves from Pt Reyes Buoy (transformed).
Hs = Significant wave height

Source: PWA, CDIP, NOAA.

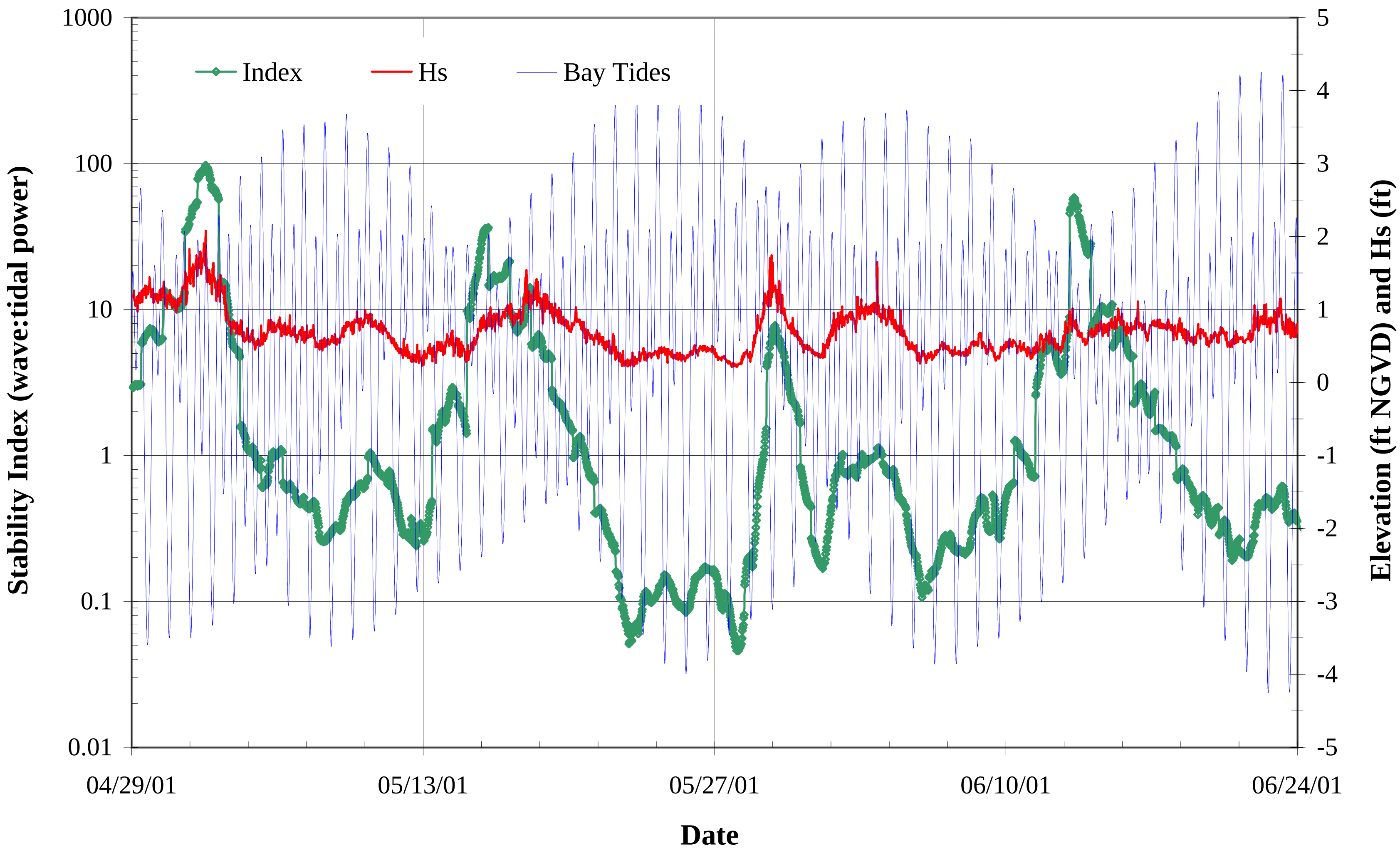
figure 5-3

Crissy Field Marsh Expansion Study

Calibration Data - May and June 2001

PWA#: 1623

PWA



Source: Quantified Conceptual Model (QCM)

Notes:
Calibrated QCM results from existing marsh.

figure 5-4

Crissy Field Marsh Expansion Study
QCM Output for Calibration Period - May and June 2001

PWA #:1623

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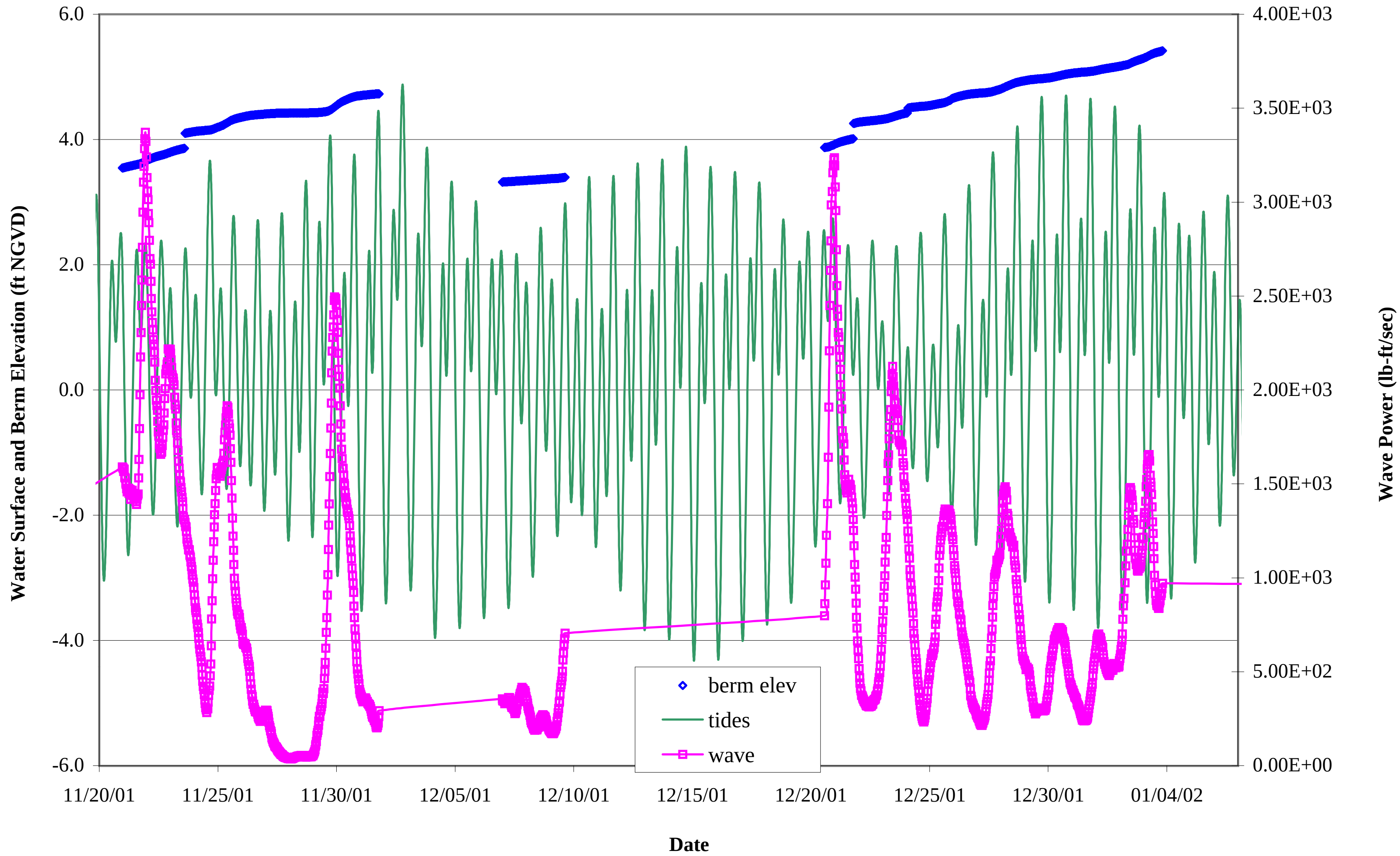

Source: Quantified Conceptual Model

Notes:
Critical elevation to induce natural breaching, as simulated by the QCM, is plotted for the winter storms of 2001-2002.

figure 5-5

Crissy Field Marsh Expansion Study

Simulated Berm Elevation During Closures of Nov. and Dec. 2001

PWA#: 1623

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6. EVALUATION OF EXPANDED WETLANDS SIZES

6.1 GEOMETRY OF EXPANDED WETLANDS

The frequency of closure was analyzed for expanded wetland sizes using the calibrated QCM, and required the geometry of these hypothetical cases to be defined. Since the model uses an estimate of the effective tidal prism in computing inlet stability, the stage-storage relationship and low water drainage elevation must be established for each wetland size analyzed. The former depends on the shape and size of the lagoon, while monitoring data presented earlier show that the latter is governed by morphology of the inlet channel. The paragraphs below describe how each of these parameters was established for input to the QCM.

6.1.1 Expanded Lagoon Geometry

Although sedimentation over the tidal shoals and migration of the inlet channel was rapid following tidal restoration, the site currently appears to be in a dynamic equilibrium as a sandy coastal lagoon and in a transitional state as it evolves more slowly into a vegetated marsh. Therefore, the expanded wetland sizes were assumed to have the same distribution of sub- and inter-tidal areas as the existing lagoon, since an expanded site would likely induce short-term and rapid adjustments until a similar distribution of habitat is achieved (the time scale associated with evolution of a mature vegetated marsh is much longer.). This assumption allowed for a simple scaling of the existing storage capacity of the lagoon. For example, it was assumed that a wetland twice the size of the existing lagoon would have a basin area of 28 acres at MHHW (the current lagoon has an approximate footprint of 14 acres at MHHW) and twice the area at lower elevations within the tide range.

Although ecological values could possibly be enhanced by creating an expanded wetland with gentler side slopes – resulting in a larger footprint for the same tidal prism – project constraints have previously limited the area available for tidal restoration and resulted in the relatively steep side slopes in the existing Crissy Field tidal marsh. For the sake of consistency, this study assumes that expanded wetlands will have the same stage-storage characteristics as the existing Crissy Field marsh (i.e. the ratio of tidal prism to marsh area has been kept constant). The actual design characteristics of any expanded Crissy Field tidal marsh will be determined in a subsequent planning process to be conducted by the Trust, NPS, and Parks Conservancy.

The long-term morphology is likely to change the stage-storage characteristics of the constructed lagoon. However, monitoring data collected during the first few years (PWA, 2001a; 2001b) show very little deposition of estuarine sediments, and we expect tidal inlet processes to govern for at least the next couple of decades. The evolution of the lagoon is discussed in more detail later in this report.

6.1.2 Low Water Drainage of Expanded Wetlands

The effective tidal prism in the lagoon is strongly influenced by the amount of muting at the inlet. For example, the effective diurnal tidal prism of the existing 14-acre lagoon would increase from approximately 17 ac-ft to about 46 ac-ft if the inlet did not affect the tide range in the lagoon. Tidal prism is plotted against low water elevation in the lagoon for the existing and expanded wetland sizes in Figure 6-1. Monitoring data reveal that muting is a result of elevated low water levels in the lagoon, with no appreciable difference in high water levels. Therefore, a reasonable estimate of low water elevation for enlarged wetland size must be established before the QCM can be applied to these hypothetical cases. Since the maximum thalweg elevation of the inlet channel controls the low water elevation in the lagoon, we outline an approach below to estimate the amount of downcutting at the inlet throat and use this as a surrogate for changes in the lagoon low water elevation.

Channel depth is expected to increase with the size of the wetland, in response to greater tidal prism and an increase in tidal currents in the inlet channel. As described by Dean and Dalrymple (2002), changes in the equilibrium cross-sectional area at the inlet throat produced by increases in tidal prism may be estimated by differentiating tidal prism relationships. In the present study, the relationship proposed by Hughes (2002) based on equilibrium discharge and scour depth was applied to Crissy Field. The cross-sectional area of the inlet channel, A_e, is related to the effective tidal prism by:

$$A_e = 0.65 k_a (C_I P)^{8/9}$$

where

$$C_I = \frac{W^{1/8}}{\left[g(S_S - 1)\right]^{1/2} d_e^{3/8} T}$$

W is the inlet width at mean tide level, T is the tidal period, d_e is the median grain size, g gravitational acceleration, k_a is an empirical coefficient (with a best-fit value of 1.34), and P is the effective tidal prism.

Changes in the predicted cross-sectional area may be found by differentiating the equilibrium expression and multiplying by the change in tidal prism:

$$dA_e = \frac{\partial A_e}{\partial P} dP = \left[0.58 C_I P^{-1/9}\right] dP$$

here dA_e and dP are changes in cross-sectional area and tidal prism, respectively. The above equation was used to determine the changes in equilibrium cross-sectional area of the inlet throat. Due to the strong damping of the tide signal by the inlet, the above tidal prism relationship is applied to the cross-sectional area below the lagoon mean tide level (MTL_{lagoon}). Figure 6–2 shows, at a conceptual level, how the tidal prism relationship above was applied at Crissy Field. Agreement between the measured and predicted values of cross-sectional area is good, as shown in Figure 6–3, giving confidence in the application of the above tidal prism relationship.

Assuming that the width-to-depth ratio of the inlet throat remains the same, changes in depth of the throat can be estimated from:

$$\frac{h_{new}}{h_{old}} = \sqrt{\frac{A_{e\,new}}{A_{e\,old}}}$$

where h is the maximum depth at the throat, measured below MTL_{lagoon}. For the purposes of the present study, the amount of downcutting ($dh = h_{new} - h_{old}$) at the throat is assumed to extend to the thalweg as it crosses the flood shoal. This approach was applied for a range of wetland size and results are summarized in Table 6-1, along with the estimated effective tidal prisms. Although the effective tidal prisms plotted in Figure 6-1 are computed over a range of water levels, the estimated values of lagoon low water elevations are restricted to the upper half of the bay tide range and limit the effective tidal prism.

Table 6-1. Estimated Low Water Elevation and Tidal Prism of Expanded Wetland Sizes

Wetted Area at MHHW (acres)	Estimated Lagoon Low Water Elevation (ft NGVD)	Estimated Effective Mean Diurnal Tidal Prism (ac-ft)
14	% 1.50	17
18	% 1.28	24
21	% 1.08	31
25	% 0.89	39
28	% 0.72	47
32	% 0.57	56

6.2 CLOSURE POTENTIAL OF EXPANDED WETLAND SIZES

The calibrated QCM described above was applied to various expanded wetland sizes in order to determine the minimum size required to maintain continuous tidal action. The frequency of closure for intermediate wetland sizes was also established in order to assess the level of maintenance required if project constraints limited future expansions of the lagoon at Crissy Field to a footprint smaller than that required to naturally maintain tidal action. All of these various wetland sizes were analyzed by simulating inlet stability from 12/06/1996 to 09/30/2002, the period over which historical weave and tidal data were available and after dynamic equilibrium was achieved.

6.2.1 Minimum Wetland Size

Stage-storage curves representative of expanded wetland sizes were applied to the QCM until no closures were predicted over the simulation period. Through a trial and error approach, we determined the minimum wetland size required to naturally maintain continuous tidal action over this period to be about

32 acres, approximately 2¼ times its existing size. About 0.93 ft of downcutting is expected for this size of wetland, resulting in low water elevation of about +0.57 ft NGVD and an effective tidal prism of approximately 56 ac-ft.

6.2.1.1 Model Sensitivity

Natural systems exhibit a tremendous amount of variability, especially systems as dynamic as small tidal inlets. For example, cross-sectional areas of inlet channels can vary significantly during a single tidal cycle and between spring and neap tides (Goodwin and Williams, 1991; DeTemple, Battalio, and Kulpa, 1999). Therefore, the equilibrium areas predicted by tidal prism relationships should be interpreted as nominal time-averaged values. Since these predictions were used in the present study to estimate the low water elevations in expanded wetlands, a sensitivity analysis was carried out to assess the importance of these uncertainties.

Sensitivity runs were carried out for the 32-acre lagoon by varying the low water elevation. A reduced amount of downcutting was assumed, and the same stage-storage curve was applied to the QCM. We ran simulations assuming the low water in the lagoon dropped by only 0.62 ft and 0.31 ft, instead of the estimate 0.93 ft. Results from these QCM sensitivity runs are summarized in Tables 6-2 and 6-3, and illustrate how sensitive closure frequency is to the amount of downcutting along the thalweg of the inlet channel. The intermediate downcutting value of 0.62 ft resulted in very infrequent closures. The QCM model predicted only three closures over the six-year simulation period for these conditions, all of which naturally re-opened in less than eight days. The most conservative estimate, in which low water elevations in the lagoon dropped by only 0.31 ft, lead to fourteen closures (about 2.4 closures per year). Four of these events spanned more than 14 days and required intervention to re-establish tidal action.

Table 6-2. Simulated Closures for 32-acre Marsh and 0.62 ft of Downcutting

Closure	Dates		Days	Index	Wave Power	Tidal Power	HH-1	HH-2	Berm	Breach
1	4/9/1999	4/16/1999	6.8	20.7	885.6	42.8	2.00	3.64	3.42	Nat
2	5/9/1999	5/13/1999	4.1	12.4	475.4	38.4	1.80	3.27	3.09	Nat
3	4/26/2000	5/3/2000	7.3	12.3	663.2	54.0	1.54	3.43	3.21	Nat

Table 6-3. Simulated Closures for 32-acre Marsh and 0.31 ft of Downcutting

Closure	Dates		Days	Index	Wave Power	Tidal Power	HH-1	HH-2	Berm	Breach
1	4/19/1999	4/23/1999	3.7	14.9	1183.8	79.6	1.89	3.36	3.30	Nat
2	11/26/1998	11/29/1998	3.1	12.1	1561.9	129.3	2.30	4.66	3.99	Nat
3	12/9/1998	12/23/1998	14.0	12.2	1255.4	102.8	2.08	2.21	4.28	Mech
4	4/9/1999	4/16/1999	6.8	12.2	885.6	72.8	2.00	3.64	3.43	Nat
5	5/9/1999	5/13/1999	4.1	24.7	475.4	19.3	1.80	3.27	3.08	Nat

Closure	Dates		Days	Index	Wave Power	Tidal Power	HH-1	HH-2	Berm	Breach
6	12/13/1999	12/18/1999	5.1	15.9	518.2	32.6	1.65	3.50	3.05	Nat
7	3/29/2000	4/5/2000	6.1	17.9	793.1	44.2	1.85	3.23	3.23	Nat
8	4/24/2000	5/3/2000	8.8	12.3	753.1	61.5	1.69	3.43	3.34	Nat
9	12/2/2000	12/7/2000	5.0	12.1	834.0	69.2	2.11	3.55	3.48	Nat
10	1/29/2001	2/4/2001	5.3	12.2	1055.2	86.2	1.85	3.62	3.44	Nat
11	4/16/2001	4/30/2001	14.0	12.0	315.9	26.2	1.67	2.00	3.40	Mech
12	5/2/2001	5/16/2001	14.0	12.2	916.9	75.1	2.28	2.24	3.79	Mech
13	10/24/2001	11/5/2001	11.5	12.0	681.7	56.6	1.98	3.27	3.62	no data
14	11/21/2001	12/5/2001	14.0	12.3	2586.5	210.8	2.34	2.92	5.42	Mech

6.2.2 Intermediate Wetland Sizes

Wetland size between the existing 14 acres and minimum footprint of 32 acres were analyzed in order to predict the number of closure/breach events and to estimate the level of maintenance required to maintain adequate tidal functions (defined for purposes of this model as closures less than 14 days). Table 6-4 presents results from the QCM for these intermediate wetland sizes. As noted earlier, variability in the natural system and the approximate nature of the analysis should be considered when interpreting these results. Although the information in Table 6-4 clearly shows a relationship between wetland size and inlet performance, it is worth while to note the exact geometry of an enlarged wetland may influence the amount of potential tidal prism mobilized to maintain the inlet.

The need for mechanical intervention may be reduced slightly if the model were changed to allow for longer closures (i.e., greater than14 days). However, for the marsh sizes simulated, we do not expect the number of mechanical breaches required to vary significantly. Although longer closure durations could provide more opportunity of overtopping of the beach barrier during unusually high tides or other events, most of the variation in the tides is captured over a 14-day period. It is important to note that the acceptable duration of inlet closure may vary depending on the results of continued ecological monitoring conducted by the NPS.

Table 6-4. Simulated Closures for Intermediate Wetland Sizes During 6-Year Simulation

Tidal Prism* (ac-ft)	Wetted area at MHHW	Reduction in Low Water Elevation (ft)	Number of Closures/Breaches				
			Natural Breaching	Mechanical Breaching	Total	Closures/year	Mechanical Breaching /year
17	14	-	18	12	30	5.2	2.1
24	18	0.22	12	10	22	3.8	1.7
31	21	0.42	11	4	15	2.6	0.7
39	25	0.61	4	1	5	0.9	0.1
47	28	0.78	2	0	2	0.1	0.0
56	32	0.93	0	0	0	0.0	0.0

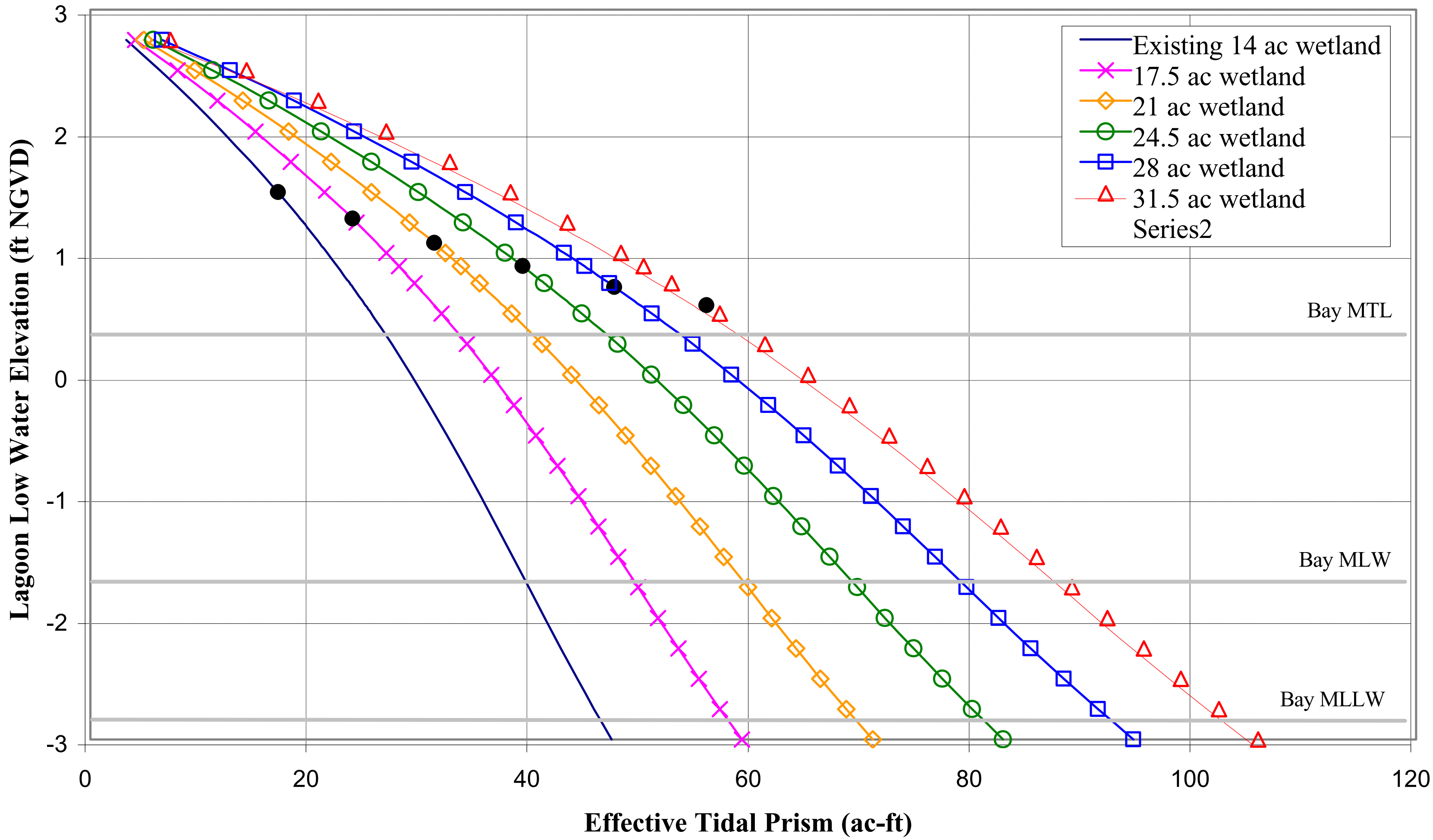
* Assumes same stage/storage characteristics as existing marsh. Simulation period is from 12/06/1996 to 09/30/2002.

6.3 EVOLUTION OF THE CONSTRUCTED WETLAND

We expect the constructed wetland to ultimately mature into a vegetated marsh and most of the remaining sub-tidal habitat to be restricted to a few tidal channels. However, observed sedimentation rates of cohesive material are very low, and the site is likely to continue functioning as a sandy coastal lagoon for at least the next several decades, with its tidal functions primarily influenced by inlet morphology and dynamics.

Figure 6–4 shows the expected siltation due to estuarine sediments over the long-term. Following several decades during which the mash maintains its existing condition, the sub-tidal and lower inter-tidal sandflats/mudflats will dimension in favor of higher inter-tidal marsh. The overall effect of sedimentation is a significant reduction in the tidal prism. The amount of high marsh at Crissy Field may be less than other sites in San Francisco Bay due to the steady wind that will generate local wind-waves in the lagoon that may slow, and perhaps halt, sedimentation in some locations higher than sandflat/mudflat elevation.

Although a large portion of the presently open water lagoon will eventually fill in with sediment after several decades, the effective tidal range is expected to increase due to the cohesive properties of estuarine mud. For example, based on hydraulic geometry relationships for mature marshes in San Francisco Bay, a 32-acre marsh would develop an entrance channel about 7 ft below MHHW. The presence of large waves, relative to other marshes in San Francisco Bay, and the strong littoral drift may limit the depth of the entrance channel. For the purposes of examining the closure potential for an evolved 32-acre marsh, we assumed the entrance channel thalweg elevation was at mean low water (–1.75 ft NGVD), or about 4.7 ft below MHHW.



Notes: Black dots denotes estimated low water drainage elevation for given wetland size. Volumes calculated from stage storage curves extrapolated from 2002 data.

figure 6-1

Crissy Field Marsh Expansion Study

Tidal Prisms of Expanded Wetlands

PWA#: 1623

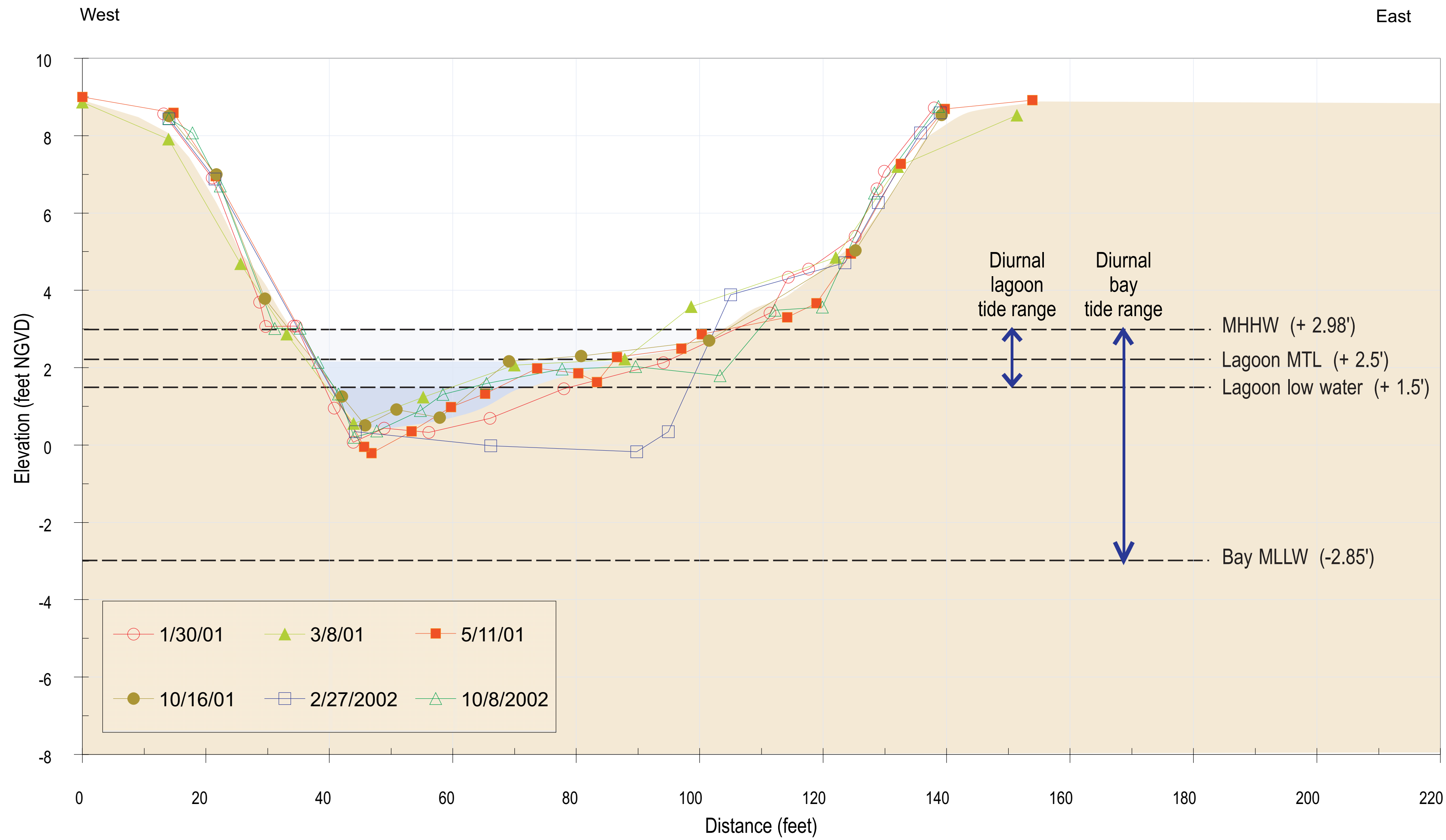


figure 6-2

Crissy Field Expansion Study

Cross-Sectional Area at Inlet Throat and Tide Levels

Note: Cross section area below lagoon MTL used in tidal prism relationship

PWA#: 1623.10 Section 6 Entrance Channel.cdr PWA

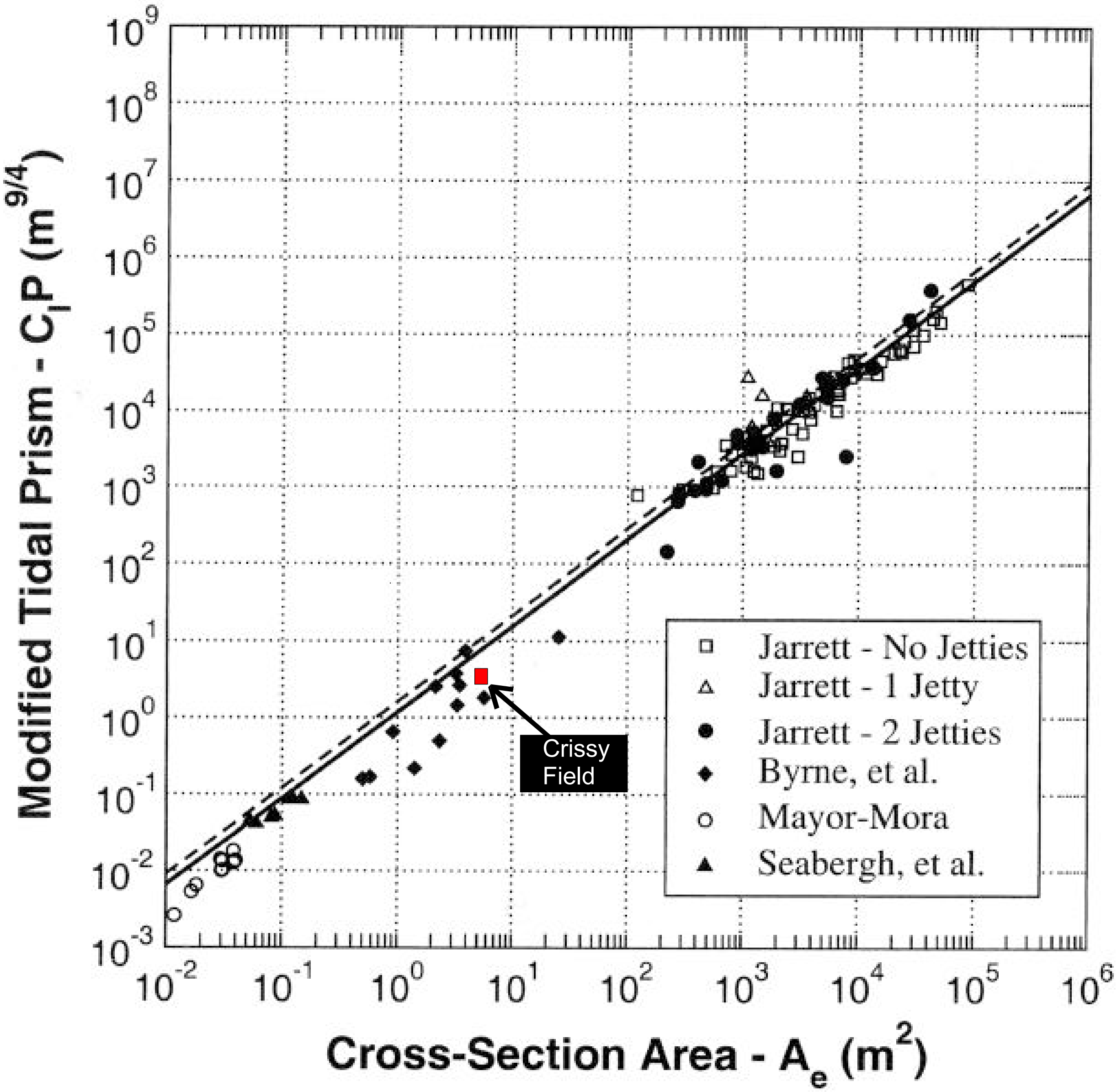


figure 6-3

Crissy Field Marsh Expansion Study

Hughes Tidal Prism Relationship and Crissy Field

PWA#: 1623

PWA

1623-00_CrissyField_Expansion_Study\Task10_Reporting\Figs\Sec6\HghsTidalPrsmRltnshp.cdr

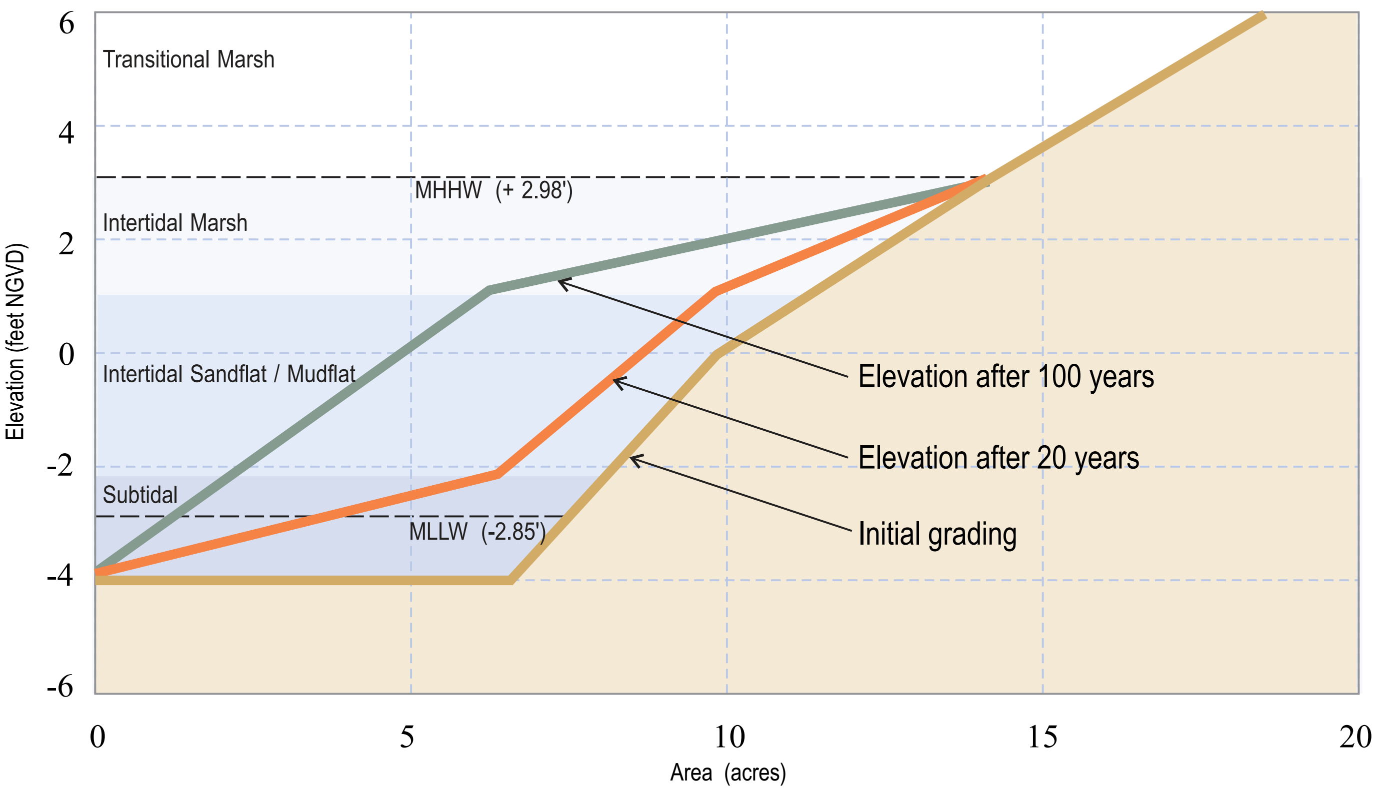


figure 6-4

Crissy Field Expansion Study

Expected Siltation at Crissy Field for Existing Wetland Site

Proj. # 1623.10 Section 6 FutureSiltation.cdr

PWA

7. A CULVERT INLET

7.1 CONCRETE ENTRANCE CHANNEL

Replacing the tidal inlet with a concrete channel (open-top culvert) would significantly reduce the risk of closure, for both the existing and expanded wetlands. This alternative would lead to much more consistent tidal flushing with less need for maintenance. However, natural tidal inlet functions and littoral transport would be lost. Longshore sand supply to the east could be reduced causing erosion to East Beach. The paragraphs below summarize modeling results used to size the culvert, and a qualitative description of the expected effects to beach processes is presented.

7.2 CHANNEL GEOMETRY AND LOCATION

Since the conveyance of the proposed concrete channel may limit the tide range inside the lagoon, PWA carried out a series of numerical simulations to determine the minimum width required to achieve full tidal action for each wetland size. Channel widths below these minimum values may restrict flow and mute the tide range. The height of the channel is determined by the tide range and invert elevation. It was assumed that the concrete entrance channel would be approximately 800 ft, extending from the interior of the wetland to approximately the –5 ft NGVD contour in the bay.

A culvert location immediately east of the existing groyne was assumed to be most practical location due to the proximity to the existing inlet and the fact that this location would minimize the groyne effect of the culvert. Culvert locations in other locations, such as at the west end of the marsh, were not considered since these alternatives would lead to more wave exposure at the mouth of the inlet and increase the potential for closure. Channel length and invert elevations assumed in the analysis are listed in Table 7-1.

Table 7-1 Channel Length, Elevations, and Roughness

Channel length	800 ft
Invert elevation at lagoon	- 4.0 ft NGVD
Invert elevation at bay	- 5.0 ft NGVD
Roughness (Manning's "n")	0.03

Observed bay tides from the Presidio tide gage and stream flow from Tennessee Hallow[3] were collected during a period of significant rainfall and high bay tides (11/15/2001 to 12/15/2001) to simulate high-flow conditions, when the discharge through the culvert is near its maximum expected value. A transient one-dimensional hydrodynamic model was applied to simulate discharge through the concrete channel and water levels in the lagoon. Channel width was varied until tidal muting was negligible and flow was

[3] 1-hour streamflow data from SD-1 measured by Kamman Hydrology & Engineering, Inc. and provided by NPS.

subcritical. Results are summarized in Table 7-2 and include the peak current velocities simulated over the spring-neap period**.**

Table 7-2. Minimum Channel Widths for Various Wetland Sizes

Wetland Size (acres at MHHW)	Tidal Prism (ac-ft)	Minimum Channel Width Required for Full Tide Range (ft)	Average Spring Peak Velocity (ft/sec)
14	47	15	2.9
18	59	15	3.4
21	71	20	3.3
25	83	22	3.4
28	94	25	2.6
32	106	35	2.9

Although channel widths less than those reported above did not mute the tide range, peak current velocities increased to supercritical values and indicate an abrupt change in hydraulic conditions as the flow transitions into subcritical levels. Since these conditions could pose a danger given the high amount of public use the facility receives, the channel width was widened until subcritical flow was present throughout the spring-neap tide cycle.

7.3 IMPACTS TO BEACH PROCESSES

A culvert will result in a different inlet and downdrift beach morphology, in response to the changed efficiency in sand trapping and bypassing as well as the associated current and wave patterns. Construction of the concrete entrance channel described above would interrupt longshore sand transport and affect the adjacent shoreline, depending on the culvert geometry and flow velocities. Since the littoral transport at Crissy Field is almost unidirectional, any culvert that extended through the surf zone would result in accretion along the updrift side (to the west) and erosion in the downdrift direction (to the east). Also, the higher velocities in a culvert would tend to discharge the sand farther offshore. Along beaches with mild slopes, natural by-passing would re-establish a continuous stream of littoral transport after some time. However, the steep nearshore slope of the bay would likely mean that the wave-induced transport would be displaced into deeper offshore waters and not remobilized. The deposited sand could accumulate and form an offshore bar that would re-connect longshore sand supply to the east, but this could take many years.

A concrete entrance would also halt the current cycle of inlet migration and spit breaching, a secondary mechanism for natural sediment by-passing that has been described in PWA 2001b. Under existing conditions, the nearly unidirectional longshore sand transport from west to east forces the mouth of the inlet to migrate eastward, and the channel elongates as it becomes nearly parallel to the shore. Wind-driven transport along the beach reinforces the wave-driven longshore transport, especially during closure. Naturally re-opening sometimes leads to a more northerly and direct channel connection to the bay, resulting in a large quantity of sand transferred from the updrift to downdrift inlet shoreline. The degree to which a culvert affects these sand transport patterns depends on the culvert geometry and location.

Maintenance of a culverted entrance could potentially be significant. A long culvert within the elevation range of the wave-affected shore face (down to about –4 ft NGVD) would act similar to a groyne and tend to reduce sand supply to the east. This could result in the need no nourish East Beach by direct sand placement, resulting in a significant recurring expense. Also, long submerged culverts (siphons) may require cleaning of barnacles and other marine organisms from the culvert walls that would otherwise reduce the hydraulic conveyance of the structure.

7.4 BENEFITS OF OPTIMIZING CHANNEL GEOMETRY

Results presented in Table 7-2 indicate that an approximately 800-ft long concrete channel can be constructed for each of the wetland sizes, with minimum width increasing with wetland size and varying between 15 to 35 feet. The impacts to adjacent shoreline could be significant, to the extent that the natural longshore sand transport is disrupted. However, these impacts could be lessened if the length of the constructed channel was limited. One possibility is to shorten the section of the concrete channel so that tidal currents are maintained at a sufficiently high velocity to maintain an opening across the ebb bar. This would preserve the natural by-passing that presently occurs at lower tide stages, when the ebb bar serves as a conduit for the longshore transport.

7.5 CULVERTS CONSIDERED BUT NOT EVALUATED

The functions of a closed-top culvert, and its impacts on East Beach, could be significantly different depending on the geometry and location of the structure. Although we did not examine this case, some general comments on the merits and drawbacks can be made.

Closed-top culverts could be designed to maintain continuous tidal action to the lagoon and minimize impacts to East Beach, but this would be at the expense of natural tidal inlet processes and wetland functions. Siphons that extended from inside the lagoon to beyond the littoral zone (probably tens of meters offshore) would allow for exchange of water without diverting sand from the littoral stream. Since sand would by-pass Crissy Field, impacts to East Beach would be minimal. However, natural inlet processes would be disrupted. For example, morphological features such as the flood shoal could not be maintained since sand transport would be eliminated. Aquatic wildlife uses would also be significantly affected, since fish passage through the closed-top culvert is unlikely.

8. IMPACTS TO EAST BEACH

Based on past monitoring data and our conceptual model of sediment transport processes at the inlet, we expect impacts to East Beach associated with expanding the lagoon to be qualitatively similar to those observed following tidal restoration in November 1999. In general, the ebb and flood shoals represent sediment sinks that disrupted sand delivery to East Beach as they evolved. Expansion of the existing lagoon will cause these tidal shoals to enlarge, and, without other action such as pre-filling the shoals, East Beach will adjust accordingly. Although the rates of erosion would diminish as the tidal shoals reach new equilibrium conditions, the resulting changes in wave action and tidal currents near the inlet would drive East Beach to a new state of equilibrium as well. Therefore, although the beach would recover some of its short-term losses and fluctuations in response to the seasonality of waves would continue, we expect long-term changes in the beach profile and shoreline to persist. The paragraphs below describe how East Beach would be affected by expanding the existing wetland and provide estimates of the amount and rates of the impacts.

8.1 EVOLUTION OF THE EBB AND FLOOD SHOALS

It is important to understand the evolution of the tidal shoals in response to increased wetland sizes since these morphologic features store sand that would otherwise continue downdrift and maintain East Beach. Additionally, the ebb shoal serves as a conduit for natural sand bypassing around the inlet. Although the geometry of the basin will affect the size of the tidal shoals, their morphology also vary in response to changes in the prevailing wave climate and other environmental factors. For example, sand transport to the flood shoal increased markedly during large wave events that occurred during medium to high tides (PWA, 2001b). The effective tidal prism, inlet geometry, sediment supply, slope of the nearshore, and the concrete groyne west of the inlet also affect development of the tidal shoals.

Monitoring activity at Crissy Field has included periodic surveys of the tidal shoals, and the cumulative change in sand volume in both the ebb and flood shoals has been plotted in Figure 4-3. These data show that sand accumulated in the flood- and ebb-tidal shoals at approximately 400 and 1,500 CY/month, respectively, before reaching equilibrium. The rate is affected by the strength of the sediment sink, which increases with wetland size and decreases with evolution toward equilibrium, and the rate of littoral sand transport.

Walton and Adam (1976) developed the following empirical relationships between tidal prism and ebb-shoal volume by studying tidal inlets along the East Coast, mostly with mild wave exposure:

$$V_{ebb} = \forall\ P^{1.23}$$

where, V_{ebb} is the volume of the ebb bar in CY, P is the tidal prism in ft^3, and $\forall$ is an empirically-derived coefficient that is a function of wave exposure. Walton and Adams suggest the values listed in Table 8-1 for $\forall$ based on their study of East Coast inlets.

Table 8-1. Values of Empirical Coefficient

Wave Exposure	∀
High	8.7×10^{-5}
Moderate	10.5×10^{-5}
Low	13.8×10^{-5}

Source: Walton and Adams (1976)

Results from this empirical relationship and monitoring of Crissy Field are plotted in Figure 8-1. The measured ebb volume is larger than that predicted by the empirical relationship, presumably because Crissy Field is an in-bay lagoon with lower wave exposure than the inlets studied by Walton and Adams.

Due to the discrepancy between the predicted and measured ebb shoal volumes, we derived a site-specific value of the empirical coefficient ($\forall_{CRISSY}$) so that estimates of ebb shoal volume could be made for expanded wetland sizes. Using the measured value of approximately 45,000 CY of sand and an effective tidal prism of 17 ac-ft, we found a value of:

$$\alpha_{CRISSY} = \frac{V_{ebb}}{P^{1.23}} = \frac{45{,}000\,\text{CY}}{17\text{ac-ft} \times 43{,}560\,\text{ft}^3/\text{ac-ft}} = 27.1 \times 10^{-4}$$

Using the above estimate of $\forall_{CRISSY}$ and the functional relationship derived by Walton and Adam, estimates of the ebb shoal volumes listed in Table 8-2 were established. The time required for the newly formed ebb shoal to reach equilibrium is estimated by assuming the measured rate of accumulation (1,500 CY/month) increases proportionally with tidal prism. Based on this analysis, a wetland expanded to about 32 acres at MHHW would produce an ebb bar about three times the current volume, and require approximately 2½ years to reach equilibrium.

The maximum rate of sand deposition is limited by the gross longshore and onshore transport rate, driven primarily by waves, and an increase in these gross rates induced by the inlet itself. Given that there is a limited sand volume in East Beach to satisfy increased gross transport and that longshore transport rate is nearly unidirectional at Crissy Field (from west to east), the net longshore sand transport rate from the west can be used as a reasonable surrogate for the gross rate. A potential long-term net transport rate at Crissy Field of about 25,000 to 33,000 CY per year has been reported previously (PWA 2001a, 2001b). Using 29,000 CY per year as an average value of the net transport rate, the maximum deposition rate indicates a longer time to attain the equilibrium geometry, which is indicated in the column "Supply Limited Time to Equilibrium" in Table 8-2. For example, the limited sediment transport rate extends the time required for the ebb shoal of a 32-acre marsh to reach equilibrium to about 5 years.

Table 8-2. Estimated Ebb Shoal Volume for Expanded Wetlands

Wetland Size at MHHW (acres)	Tidal Prism (ac-ft)	Ebb Shoal			
		Volume (CY)	% Change in Volume	Time to Equilibrium (months)	Supply Limited Time to Equilibrium (months)
14	17	45,000	n.a.	n.a.	n.a.
17 ½	24	68,800	55 %	11	10
21	31	94,200	110 %	18	20
42 ½	39	125,000	175 %	23	33
28	47	157,000	250 %	27	46
31 ½	56	195,000	335 %	30	62

n.a. = not applicable to existing wetland

8.2 CHANGES TO EAST BEACH

East Beach includes the entire shoreline from the concrete groyne (sometimes referred to as a jetty or West Jetty) on the west to the beginning of the rock revetment to the east. Significant morphological changes occurred to this section of the beach following restoration of tidal action in November 1999, and we expect impacts associated with wetland expansion to be qualitatively similar but different in magnitude. Previous reports (PWA, 2001a; 2001b) have documented changes in the profile and shoreline of East Beach from November 1999 through May 2001, a period in which the beach was adjusting to the newly constructed lagoon at Crissy Field. These adjustments included erosion of the beach east of the inlet, accompanied by rotation of the shoreline and changes to the beach profile. The rate of erosion slowed, and in some places recovered, as the system evolved to a new equilibrium. Expansion of the existing lagoon would result in further adjustments, as the system tends to a different equilibrium state in response to changes in the wave climate, tidal power, and inlet morphology.

Transects collected across East Beach show that its profile changed from a fairly uniform slope before restoration to a compound profile with a steeper upper portion, a flatter mid portion, and a steeper lower portion. Impacts were more pronounced closer to the inlet, as demonstrated by beach profiles 12-E and 13-E (Figure 8-2). (Note that the accretion shown in the 02/27/2002 and 10/08/2002 surveys was likely a result of inlet closure.) The formation of this compound beach profile suggests that sediment delivery to East Beach is reduced in the upper tide range, but natural bypassing occurs at lower water levels. At the upper tide range, flood currents divert sand into the lagoon that forms the flood shoal or accumulates in the entrance channel. Enhanced longshore transport past the inlet and inlet bypassing occurs at lower stages of the tide due to the large amount of tidal muting and formation of the ebb shoal, leading to accretion at lower elevations (PWA, 2001b). Figure 8-3 shows, at a conceptual level, these transport patterns and the expected change in the beach profile near the inlet. Note that some of the sediment transported out of the tidal inlet by ebb currents in the channel are "lost" to deep portions of the bay, however most of the sand remains in the littoral stream.

The “hinge point” in the beach profiles between the wider low tide beach and the narrower high tide beach is related to wetland size. More specifically, the elevation of this hinge point is near the inlet channel thalweg where it crosses the beach (called the beach sill). As the wetland area and tidal prism increase, the thalweg lowers and the profile hinge point lowers.

In addition to changes in the beach profile, adjustments to the shoreline of East Beach occurred in response to the diminished sediment supply downdrift of the inlet. Erosion near the inlet caused the shoreline to rotate counterclockwise, before accretion recovered some of the loss of beach width. A similar pattern of shoreline adjustments is expected following expansion of the existing lagoon, as shown conceptually in Figure 8-4.

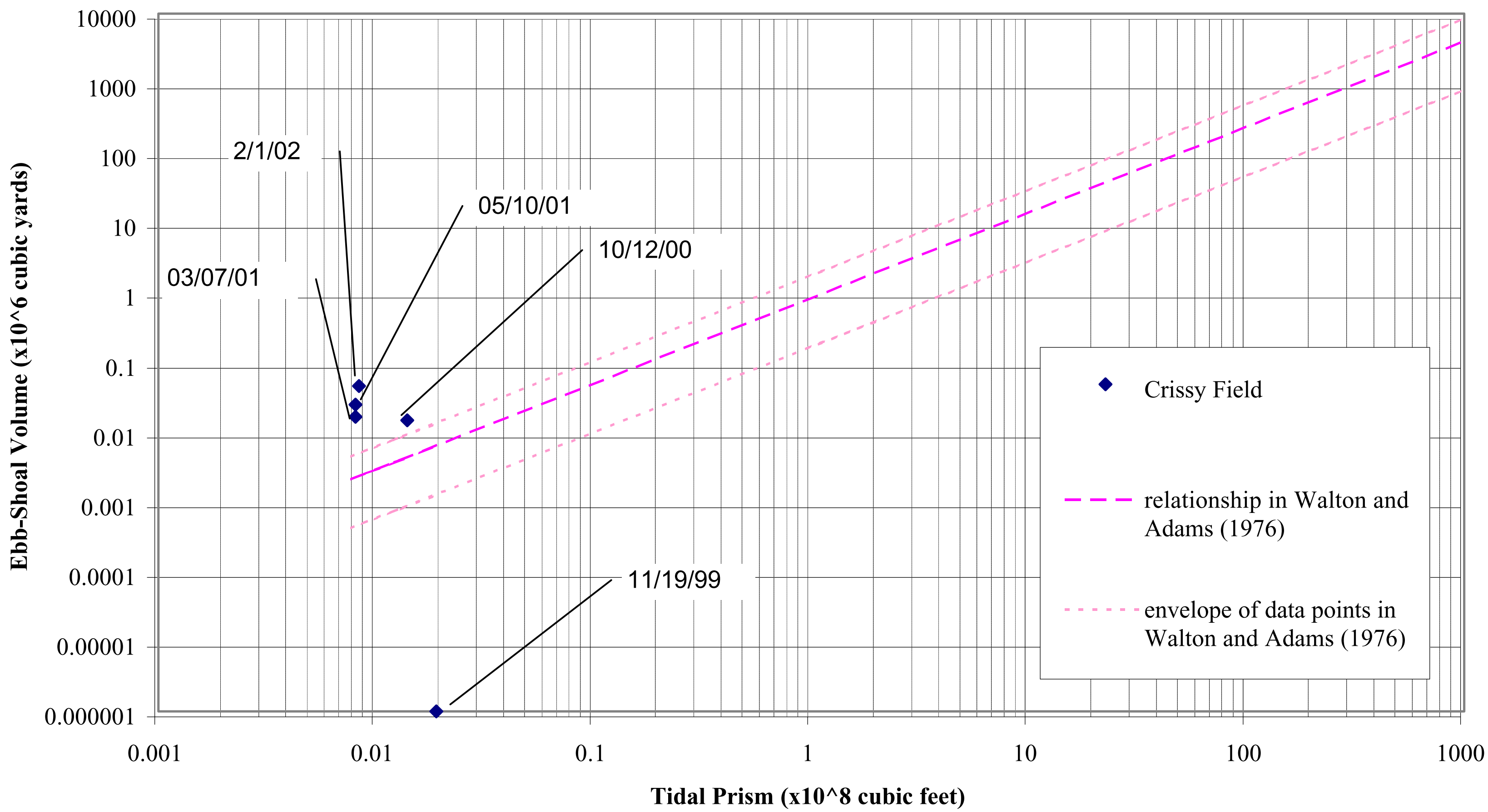
8.3 A NEW EQUILIBRIUM

Expansion of the lagoon basin is expected to induce short-term changes to the morphology of the tidal shoals and East Beach. Many of the adjustments to East Beach will be temporary, with the rates of erosion diminishing as the ebb and flood shoals evolve to new equilibrium conditions. However, these changes to the inlet morphology will affect the wave and tidal conditions, and hence the sediment transport patterns, leading to a new equilibrium state.

Reliable empirical estimates of flood shoal volumes do not exist. However, assuming that the increase in sand volume over the flood shoal is proportional to increases in the ebb shoal volumes, we can make rough estimates of the magnitude of the impacts to East Beach. Table 8-1 lists the predicted ebb shoal volumes, and gives a relative comparison among the expanded wetland sizes under consideration. For example, expanding the wetland to 21 acres at MHHW would results in a 110% increase (roughly double) in sand volume in the ebb shoal. Therefore, we can expect the expanded lagoon to accumulate roughly the same amount of sand as after the initial marsh construction, suggesting that short term impacts will be similar to those observed following tidal restoration in November 1999.

The flood shoal will grow laterally by spreading into the lagoon, but is not expected to increase in height. The length scale of the inlet channel will also increase with the tidal prism. Since the ebb shoal is “pinched” against the shore by the steep slope of the nearshore (bayshore) profile and wave action, we anticipate that most of this lengthening will be manifested in a further laterally spreading of the flood shoal into the lagoon.

Some sand has deposited in relatively deep water at the toe of the ebb shoal. This sand is believed to be delivered to the offshore during strong ebb flows that carry the sand through the narrow surf zone, and down slope. Also, the north face of the ebb shoal is steep and may slough. Monitoring data indicate a thin sand deposition has accumulated since wetland construction. We expect that this deposition rate of this offshore sand “loss” will increase with the peak ebb flow associated with a larger wetland.



Source: PWA surveys, Walton and Adams (1976)
Notes: Diurnal tidal prism calculated for Crissy Field.
Ebb-shoal volume approximated with Control Volume 2 designated by PWA.
Relationship for minimally exposed inlets used.

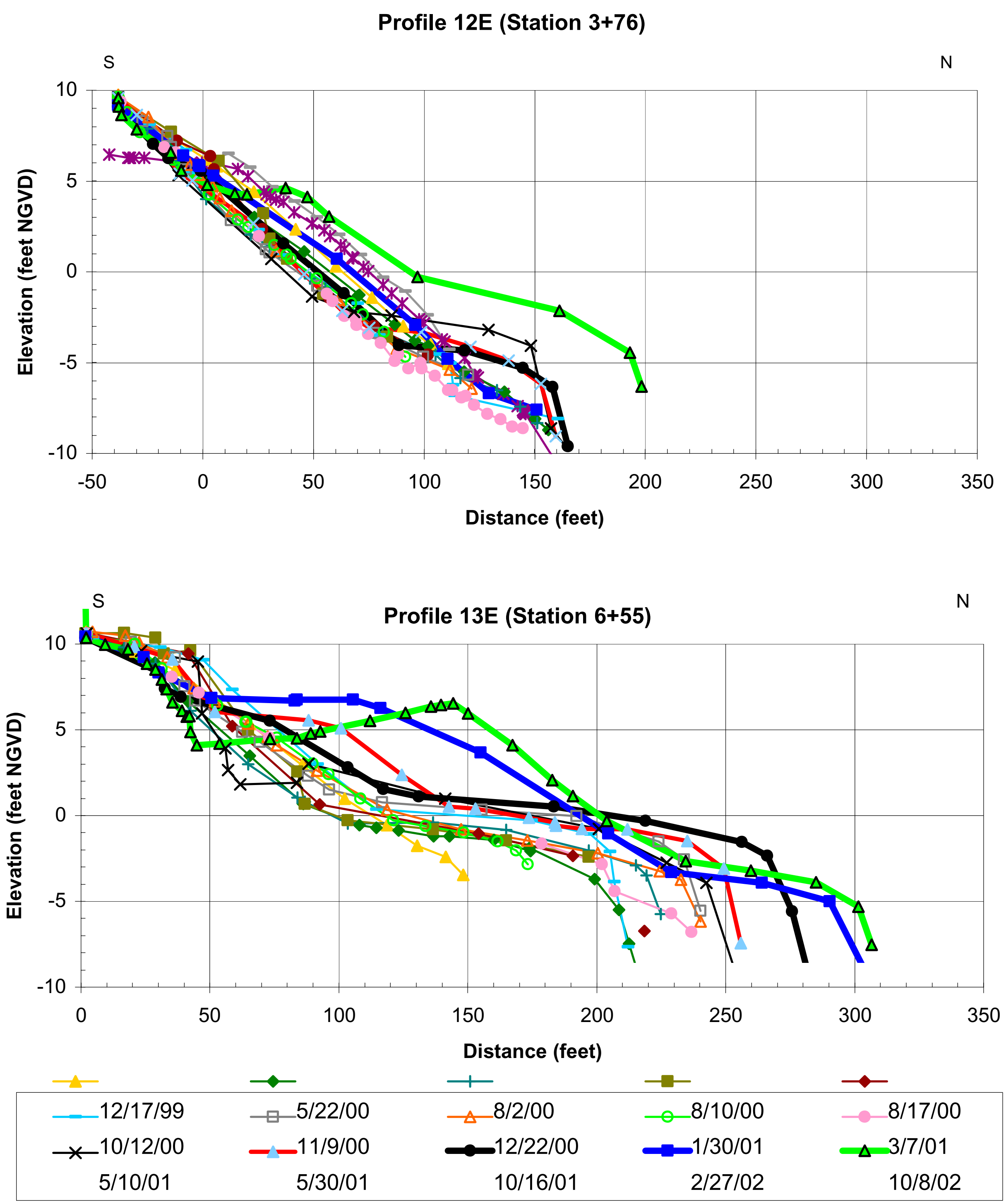
figure 8-1

Crissy Field Marsh Expansion Study

Tidal Prism versus Ebb-Shoal Volume

PWA#: 1623

PWA



Notes: Inlet was closed during 10/8/2002 survey, and 2/27/2002 survey followed mechincal breach on 1/16/2002.

Source: PWA surveys

figure 8-2

Crissy Field Marsh Expansion Study

Beach Profiles 12E and 13E

PWA#: 1623

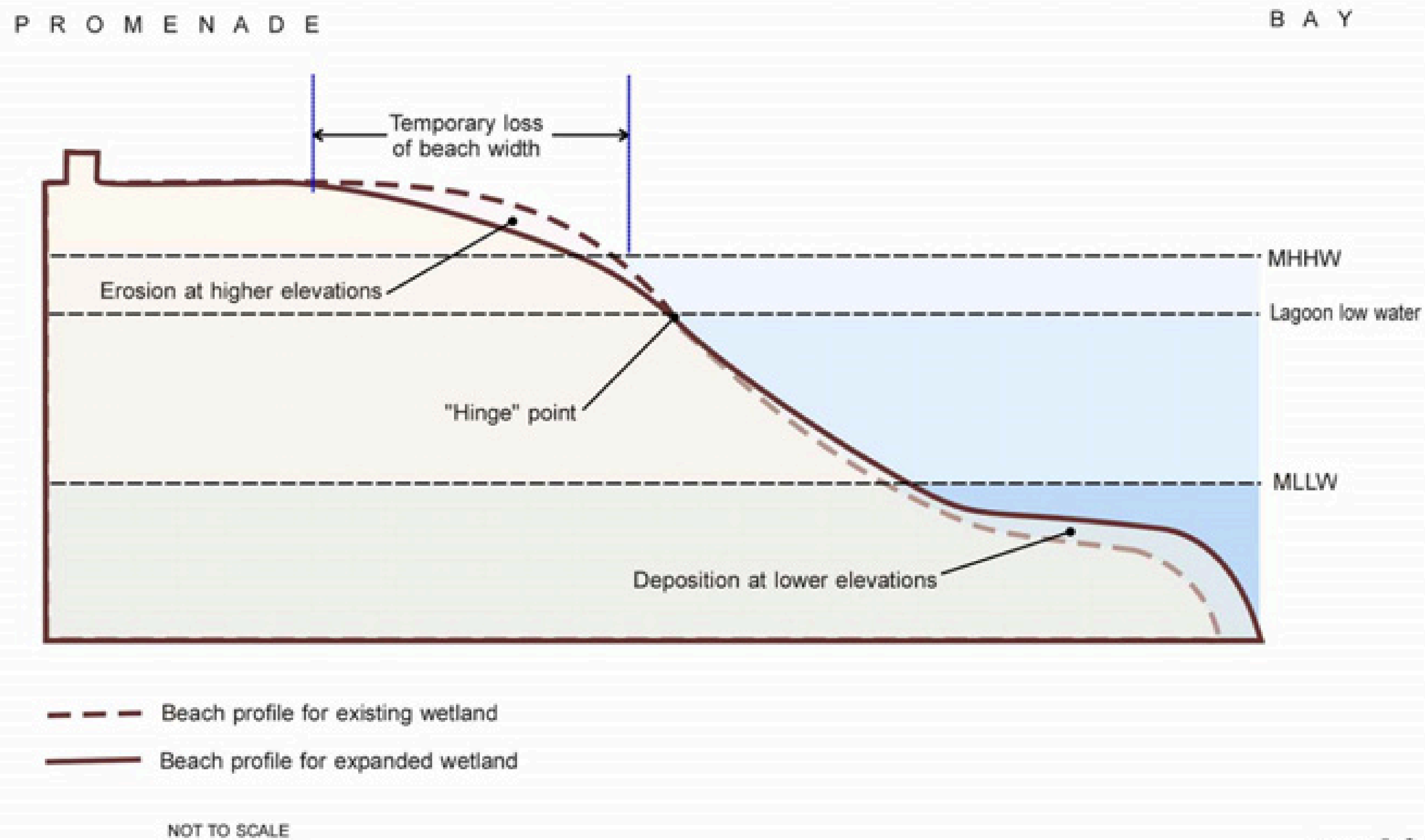


figure 8-3

Crissy Field Marsh Expansion Study

Conceptual Adjustments to Beach Profile

Proj. # 1623.00 Beach Profile2.cdr

PWA

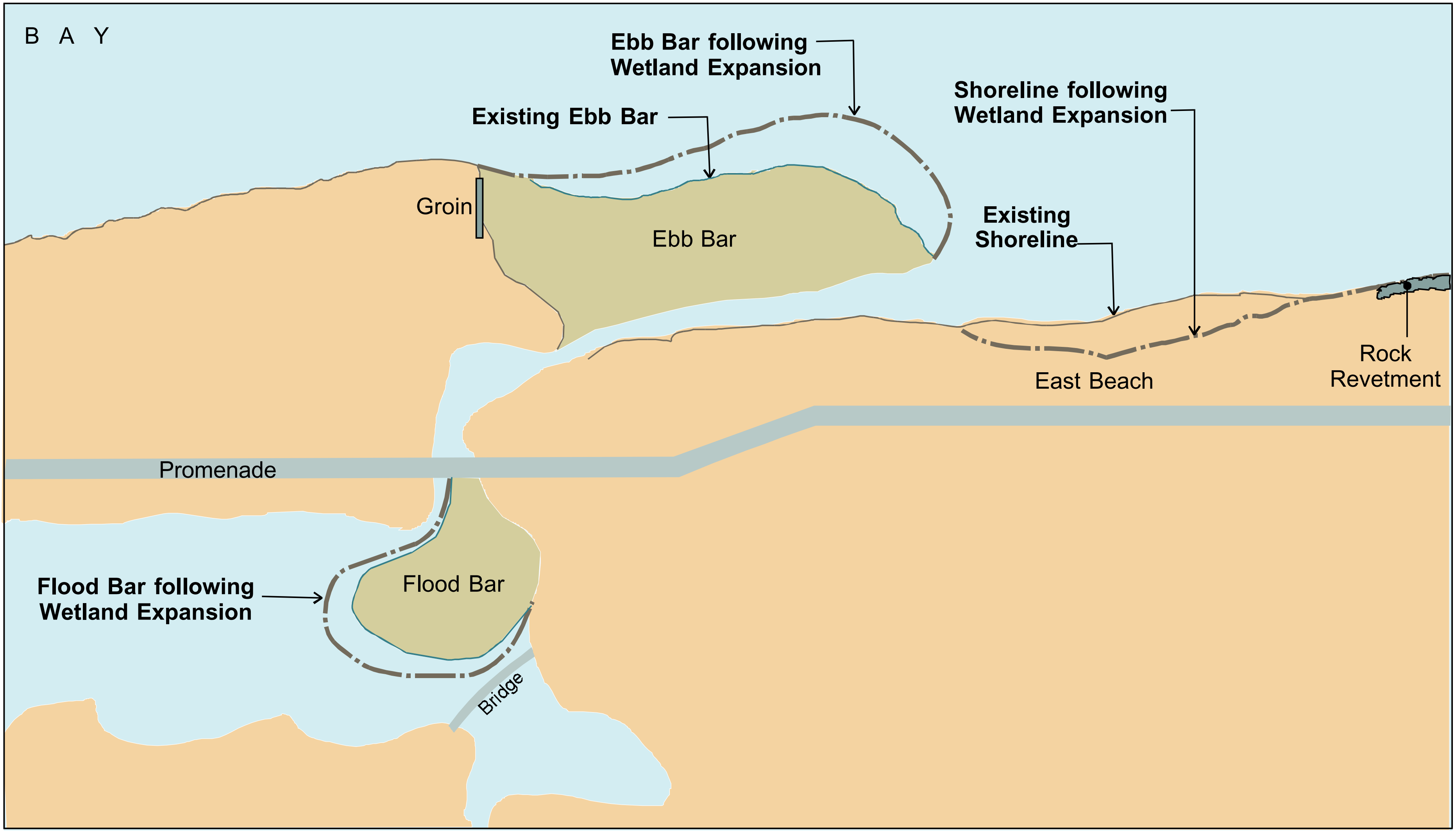


figure 8-4

Crissy Field Marsh Expansion Study

Shoreline Adjustments along East Beach

Proj. # 1623.00 SHORELINE.cdr

PWA

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Don Danmeier, Project Manager
Robert Battalio, Project Director
Philip Williams, Technical Advisor

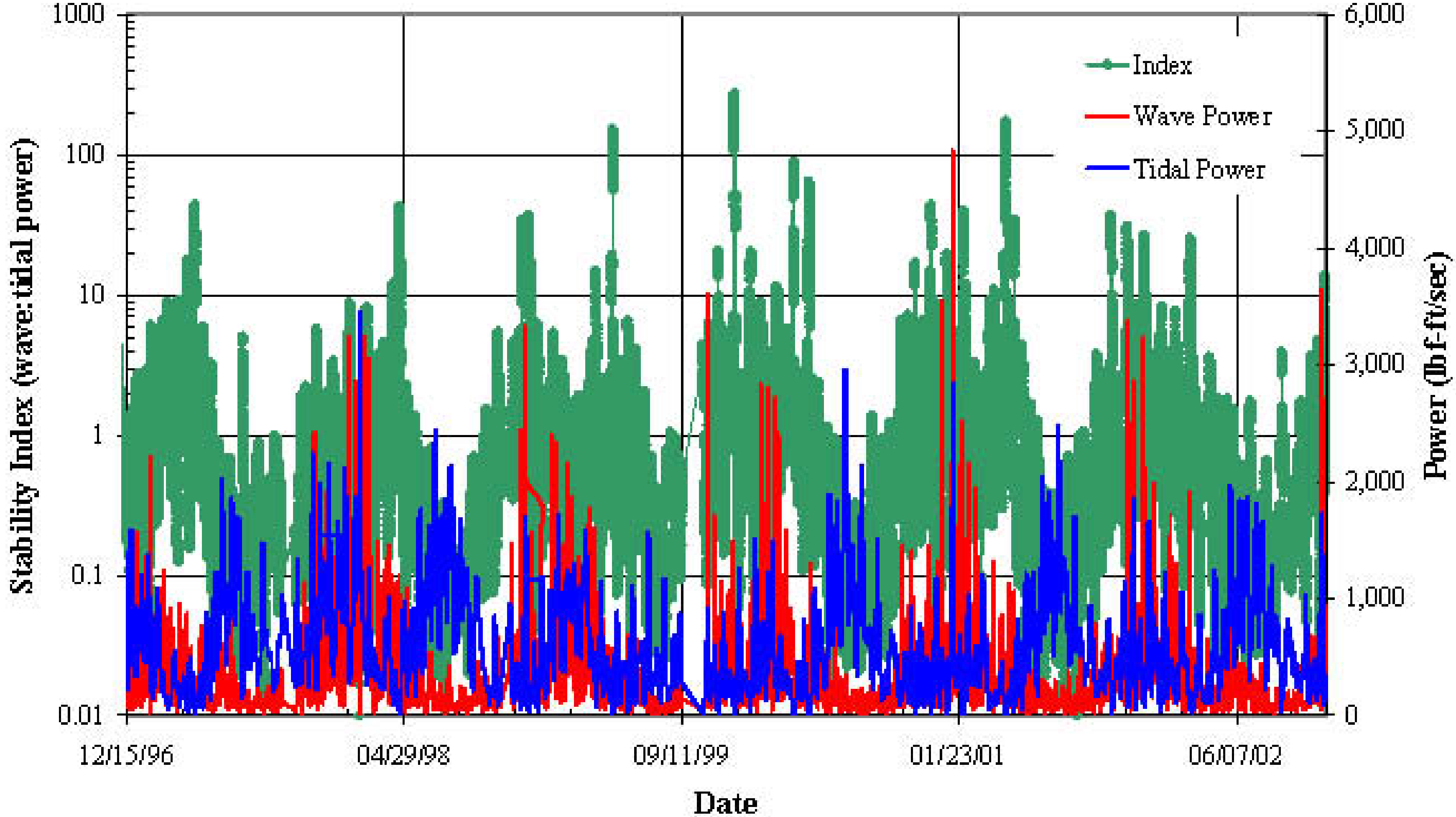
The Crissy Field study was managed collaboratively by Michael Boland (Trust), Carol Prince (Conservancy), Paul McLaughlin (NPS), and Kristin Ward (NPS).

Technical oversight was provided by an provided by an independent Technical Review Group, consisting of the following individuals:

Dr. Roberto Anima, United States Geological Survey
Dr. Rebecca Beavers, National Park Service
Dr. Andree Breaux, Regional Water Quality Control Board
Kevin Knuuti, United States Army Corps of Engineers
Michelle Levenson, San Francisco Bay Conservation and Development Commission
Michael Munroe, United States Environmental Protection Agency
Professor Robert Wiegel, University of California at Berkeley

APPENDIX A

QCM Output for Existing and Enlarged Wetland Sizes



Notes: Existing wetland size of 14 ac at MHHW, with low water elevations varying from +1.50 to +1.75 ft NGVD.

Source: Quantified Conceptual Model.

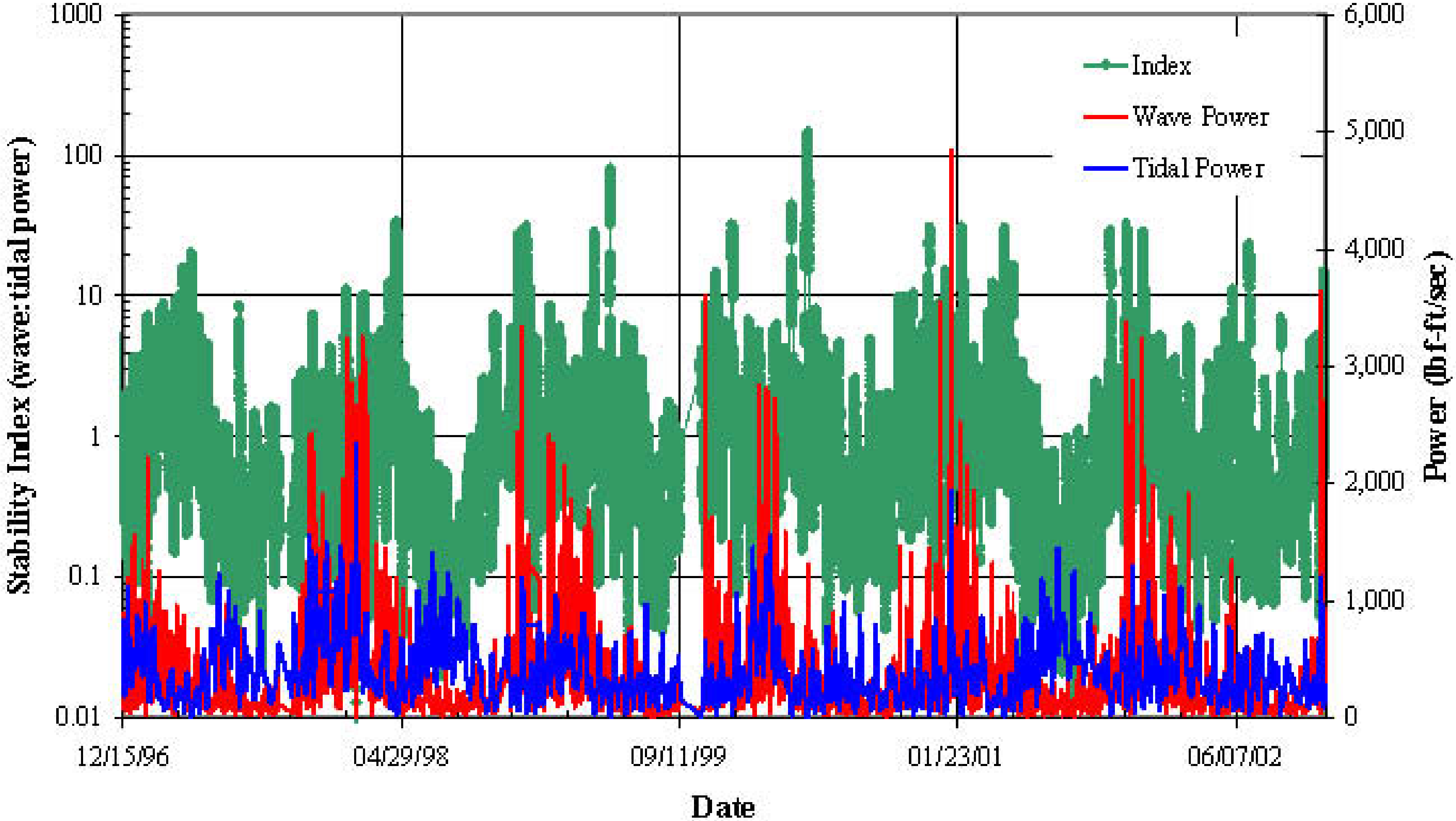
figure A-1

Crissy Field Marsh Expansion Study

Stability of Existing (14 ac) Wetland

PWA Ref 1623

PWA



Notes: Increase wetland size by 1.25 times existing, to approximately 17.5 acres at MHHW. Results assume 0.22 ft of downcutting at thalweg of inlet channel.

Source: Quantified Conceptual Model.

figure A-2

Crissy Field Marsh Expansion Study

Stability of 17.5 acre Wetland

PWA Ref 1623

PWA

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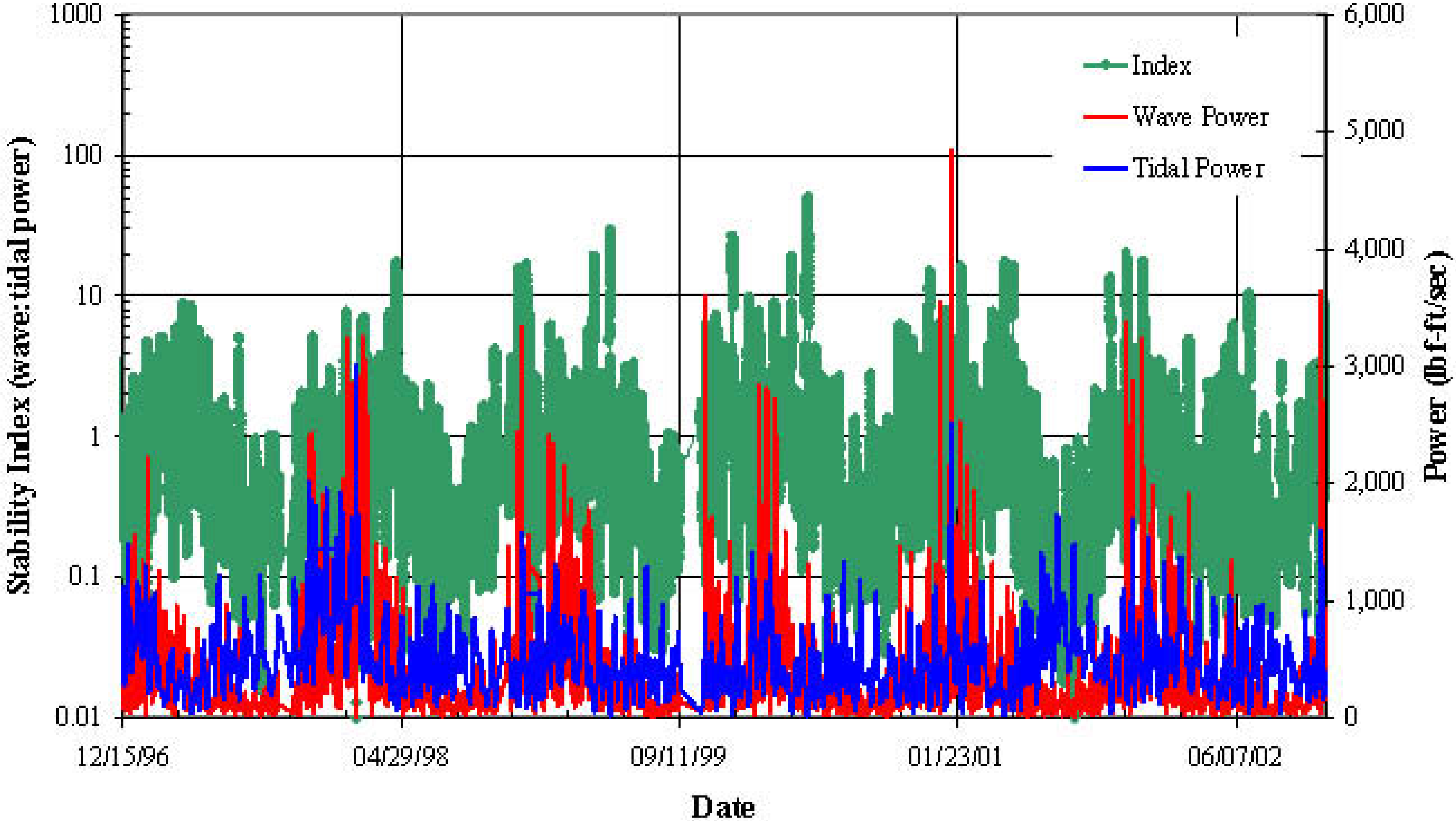


Notes: Incresase wetlands size by 1.5 times existing size, to approximately 21 acres at MHHW. Results assume 0.42 ft of downcutting at thalweg of inlet channel.

Source: Quantified Conceptual Model.

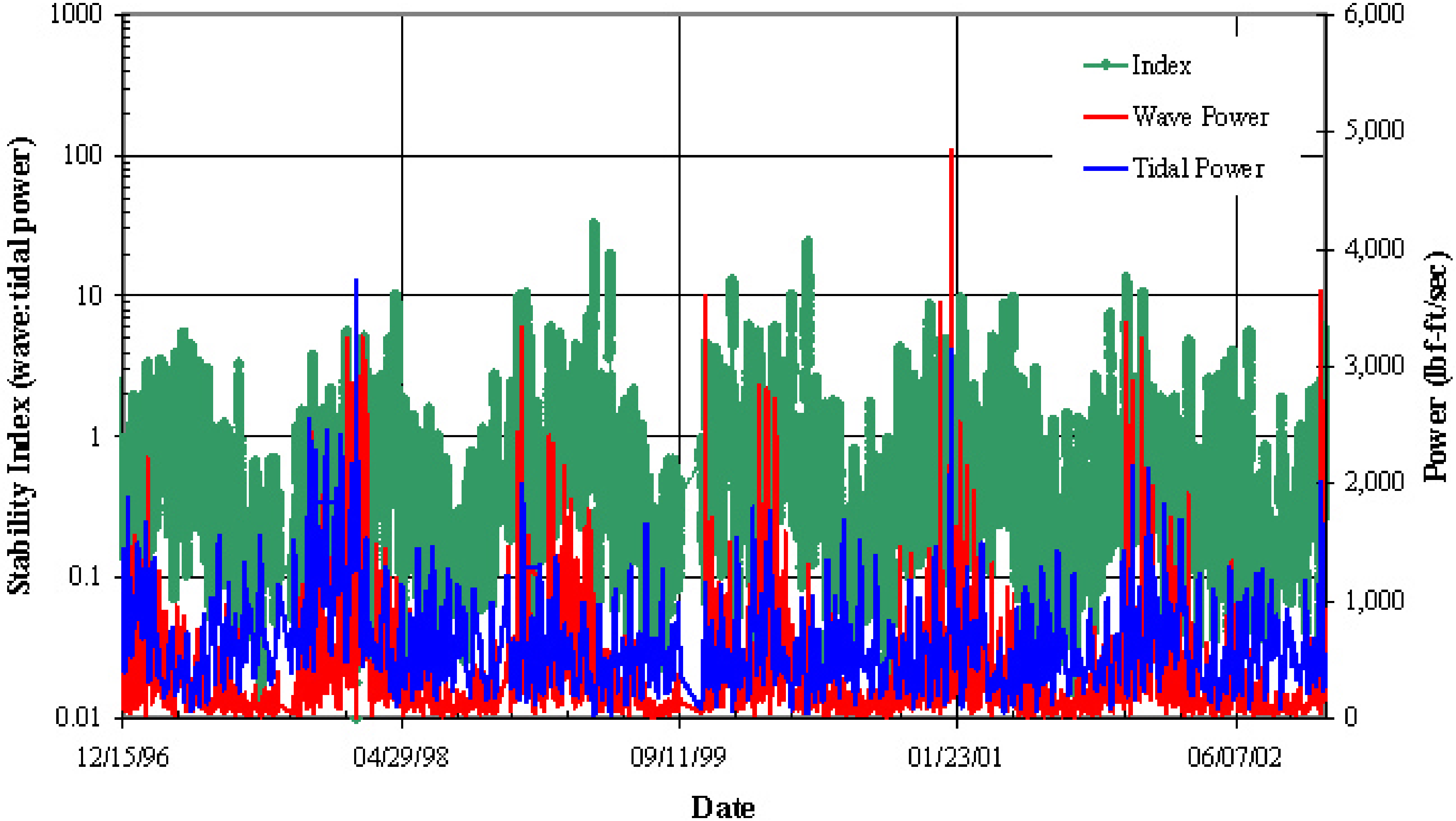
figure A-3

Crissy Field Marsh Expansion Study

Stability of 21 acre Wetland

PWA Ref 1623

PWA



Notes: Increase wetland size by 1.75 times existing, to approximately 24.5 acres at MHHW. Results assume 0.61 ft of downcutting at thalweg of inlet channel.

Source: Quantified Conceptual Model.

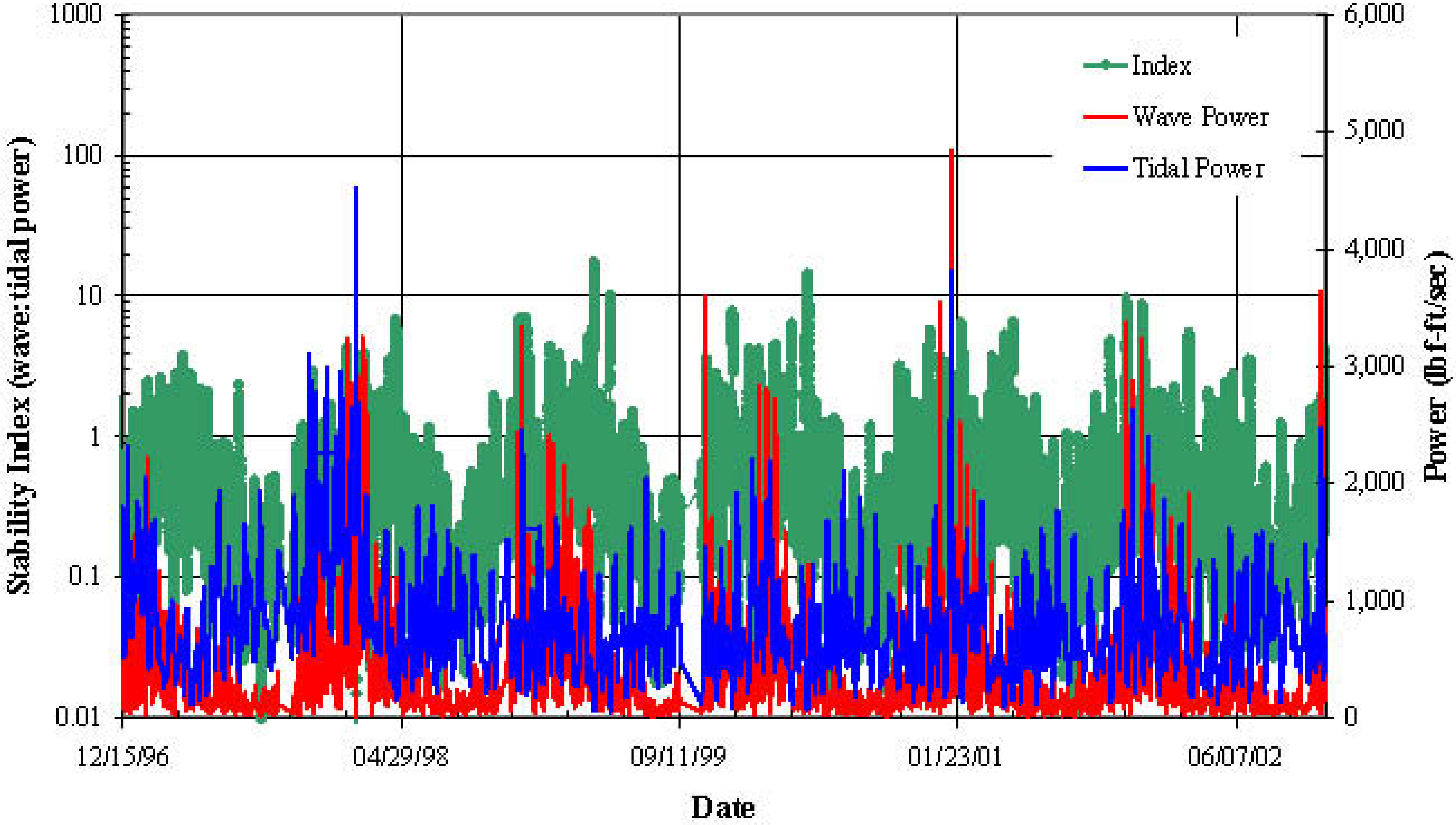
figure A-4

Crissy Field Marsh Expansion Study

Stability of 24.5 acre Wetland

PWA Ref 1623

PWA



Notes: Increase wetland size by 2 times existing, to approximately 28 acres at MHHW. Results assume 0.78 ft if downcutting at thalweg of inlet channel.

Source: Quantified Conceptual Model.

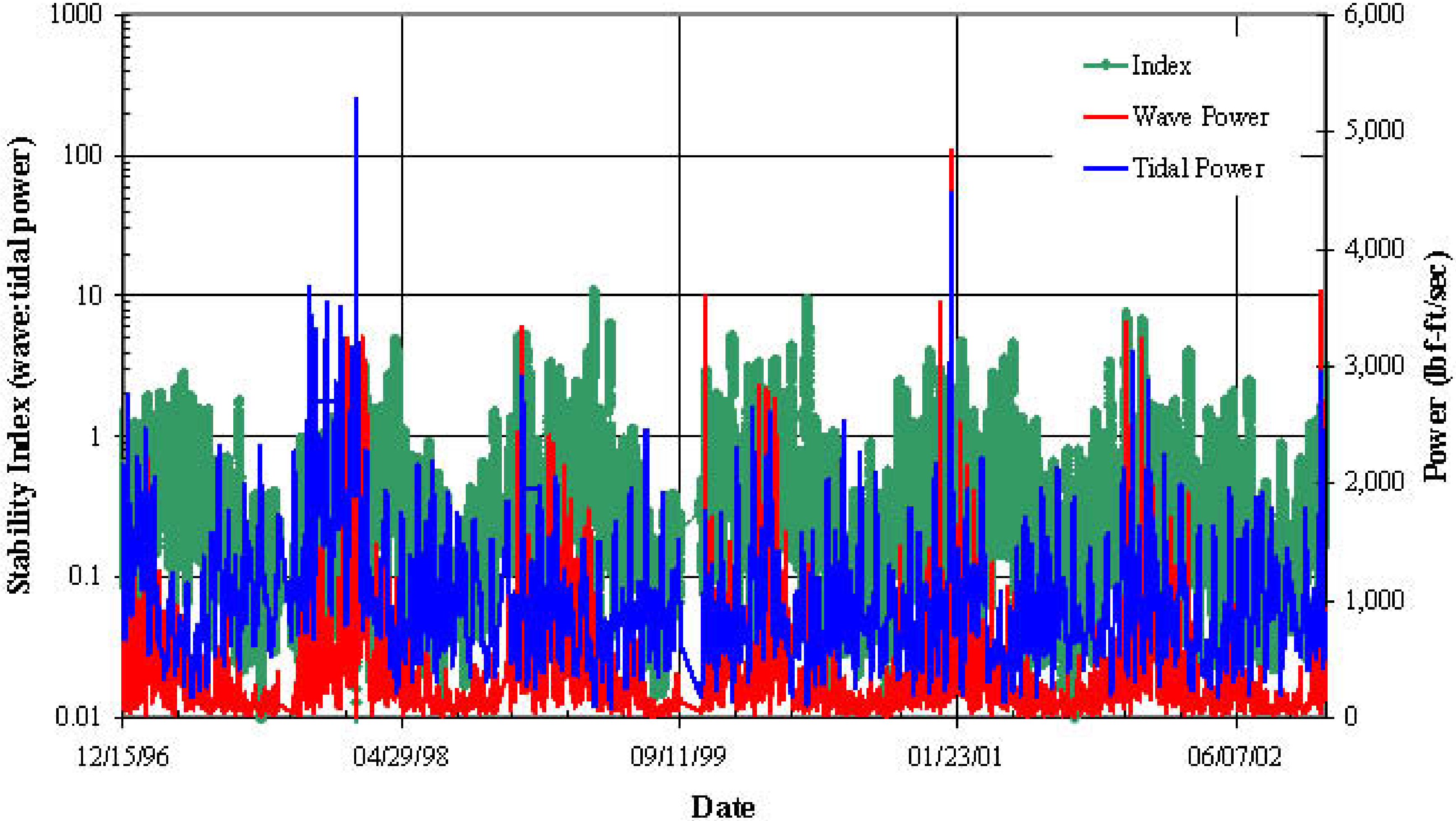
figure A-5

Crissy Field Marsh Expansion Study

Stability of 28 acre Wetland

PWA Ref 1623

PWA



Notes: Incresase wetlands size by 2.25 times existing size, to approximately 31 acres at MHHW. Results assume 0.934 ft of downcutting at thalweg of inlet channel.

Source: Quantified Conceptual Model.

figure A-6

Crissy Field Marsh Expansion Study

Stability of Minimum Wetland Size (31 acres)

PWA Ref 1623

PWA