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.

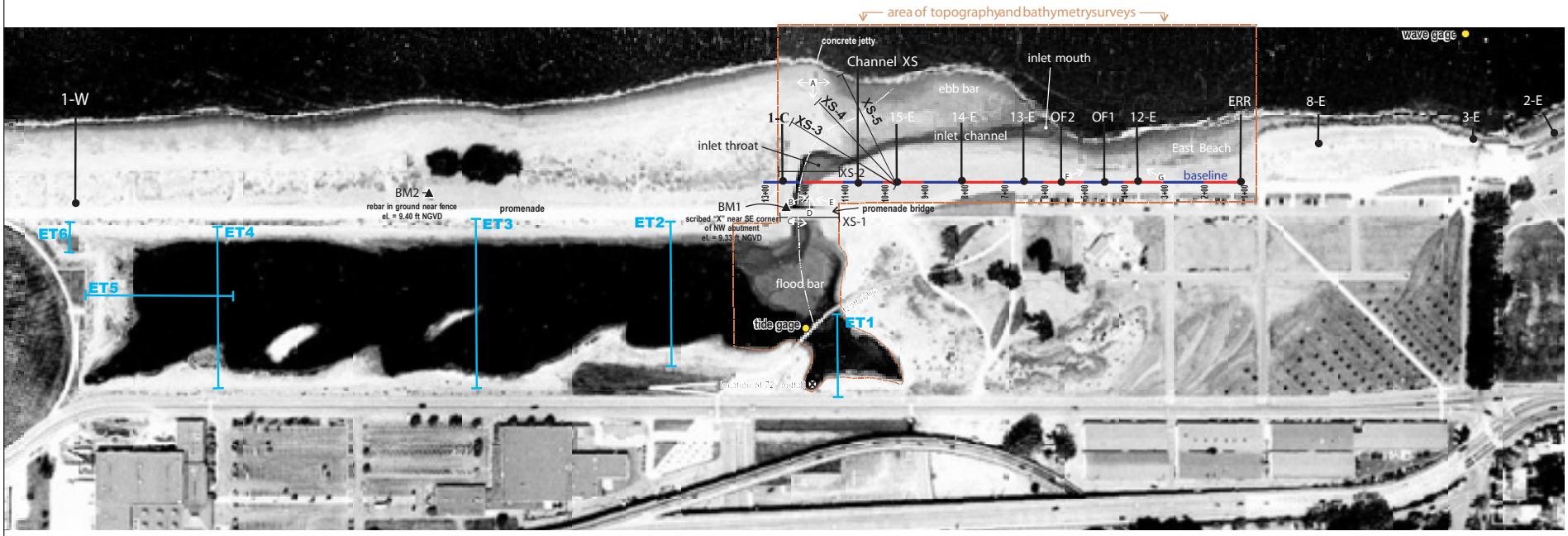
4.2.2 Breaching Mechanisms

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

= photodocumentation station

= tide gage

= beach profile

= 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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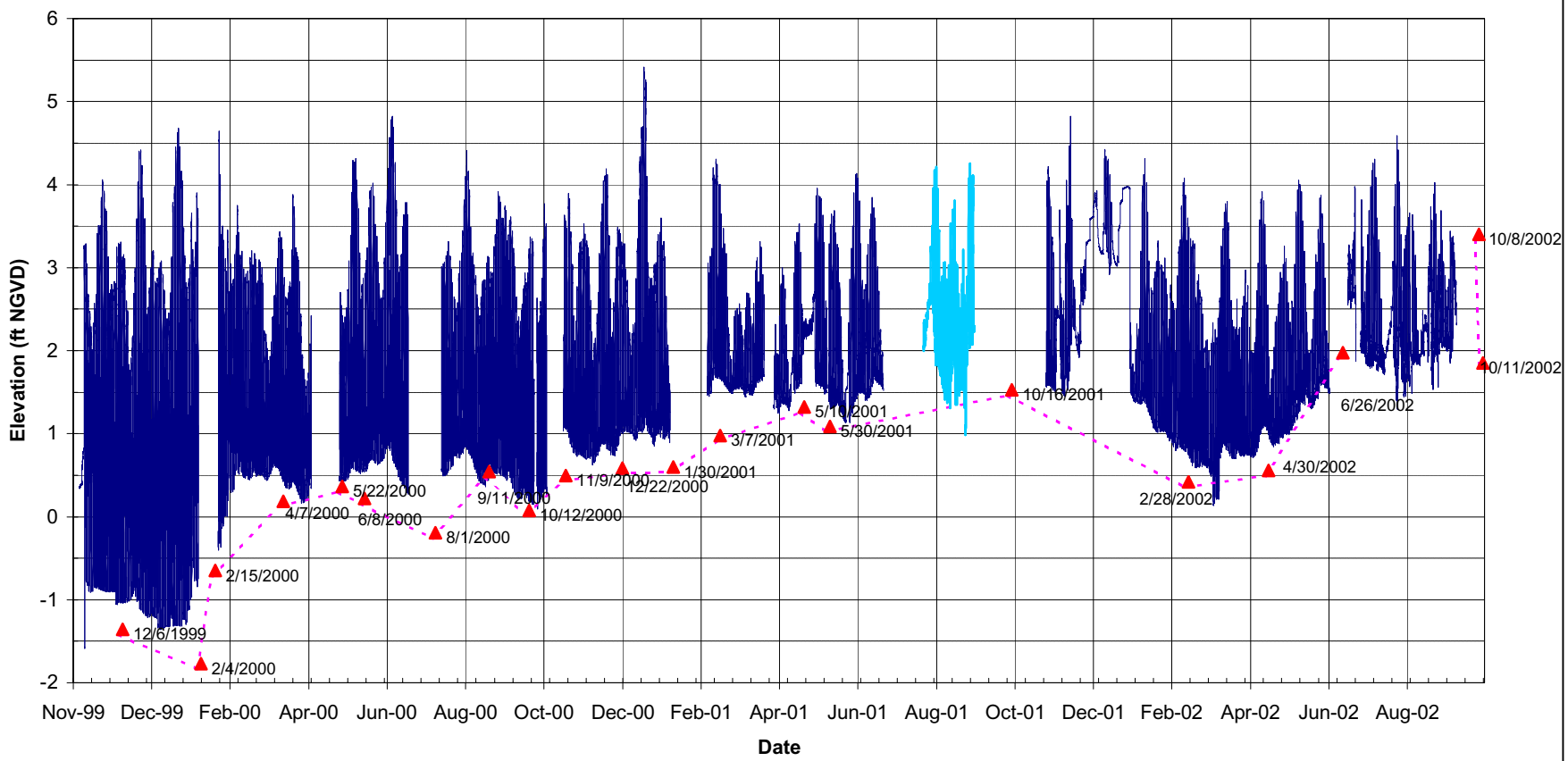
PWA



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

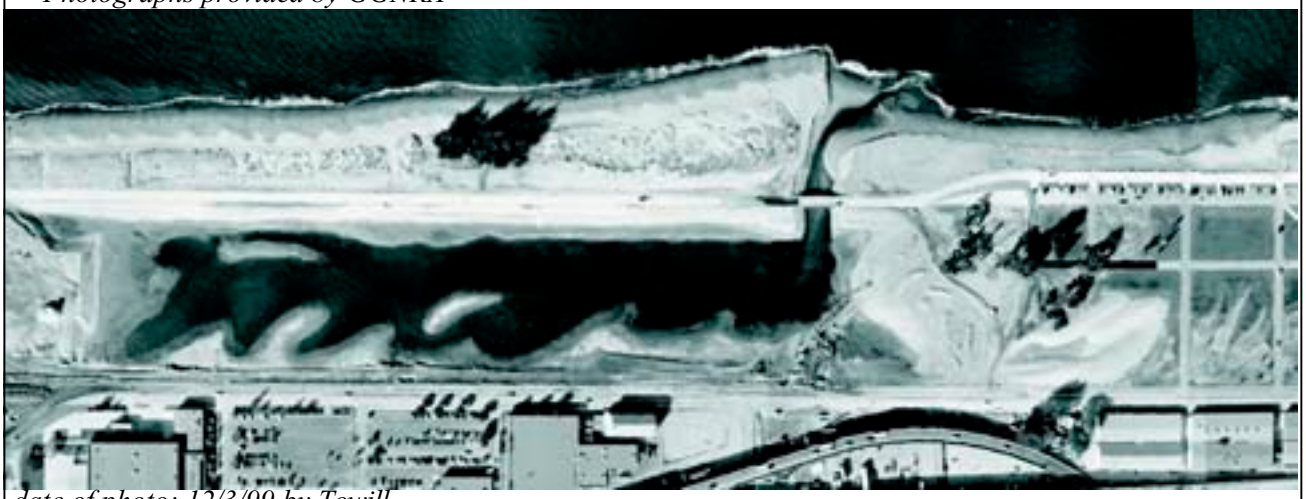
PWA

figure 4-3

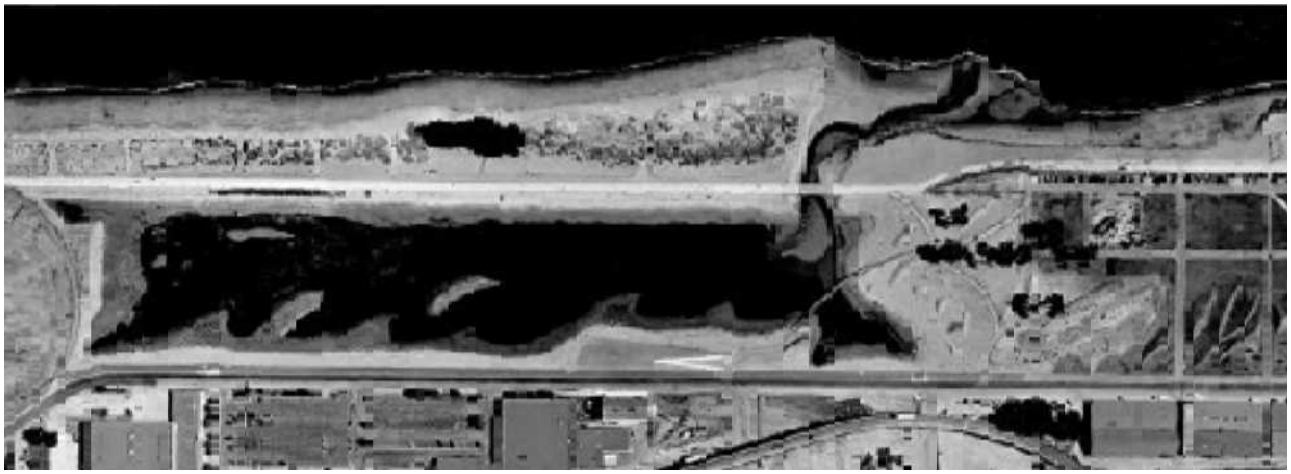
Aerial Photographs Showing Inlet Evolution

Crissy Field Marsh Expansion Study

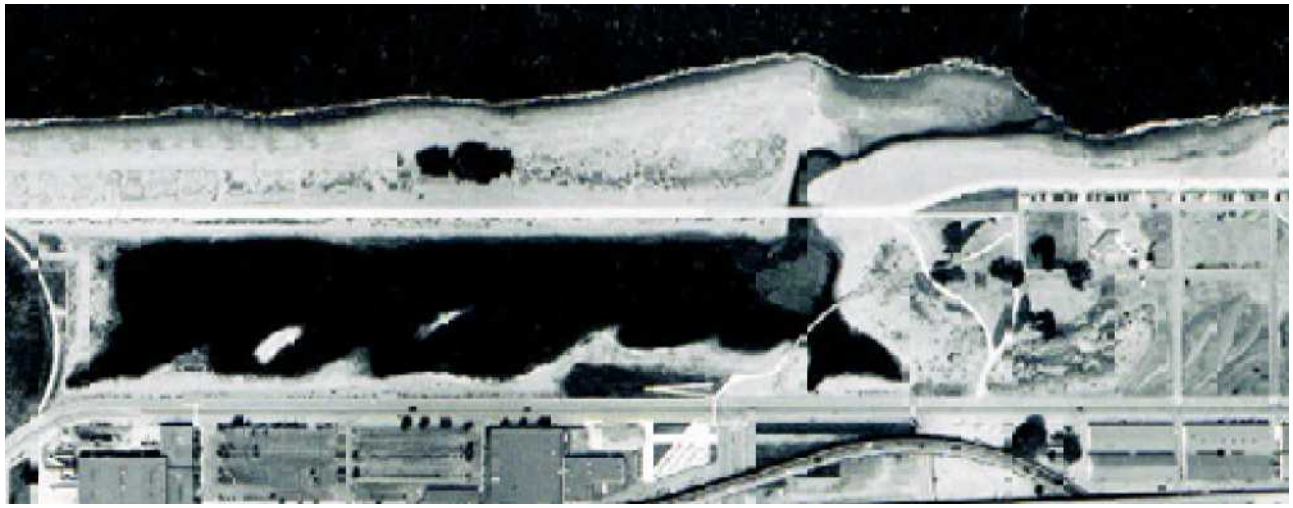
Photographs provided by GGNRA



date of photo: 12/3/99 by Towill

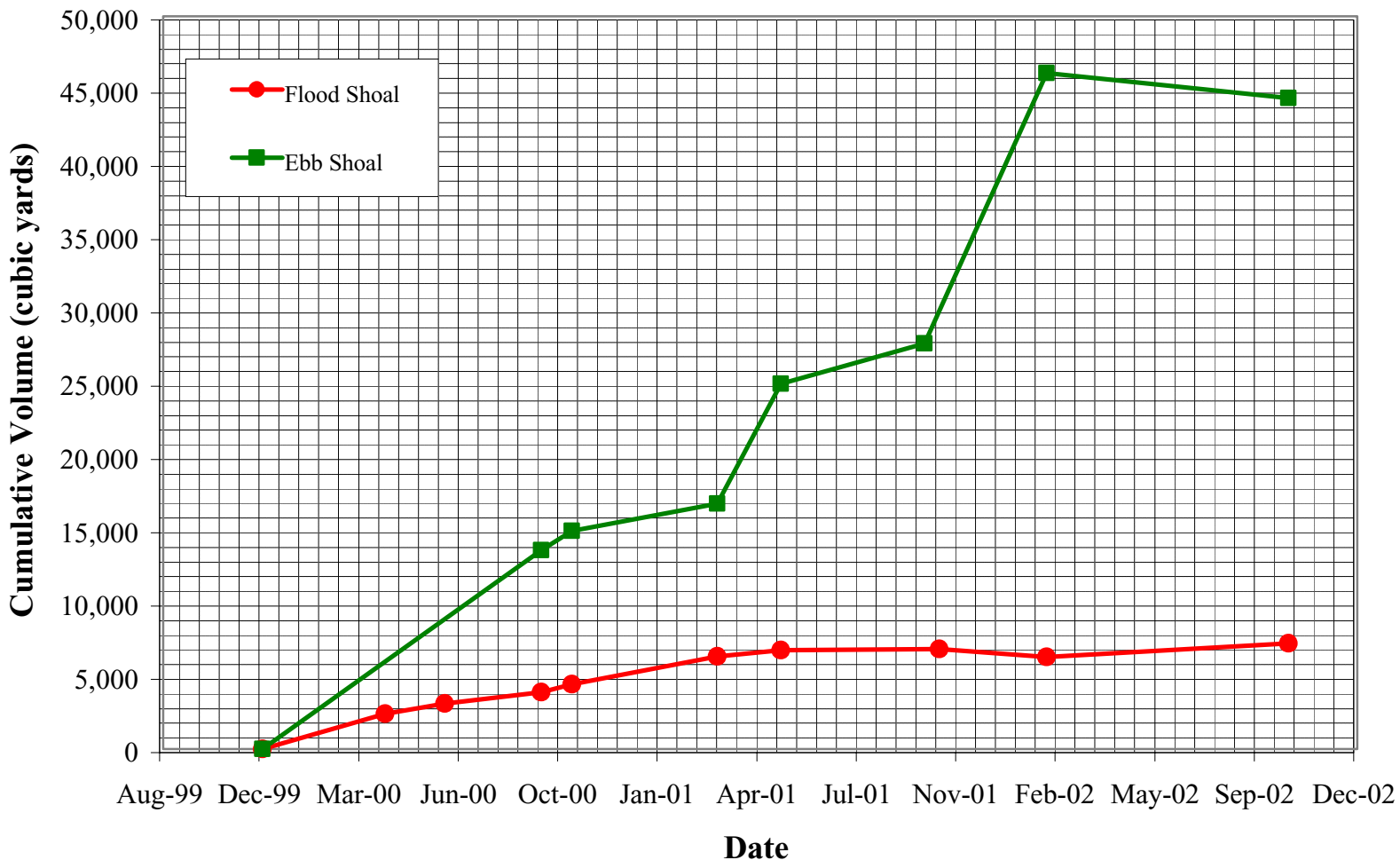


date of photo: 6/6/2000 by Towill



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.

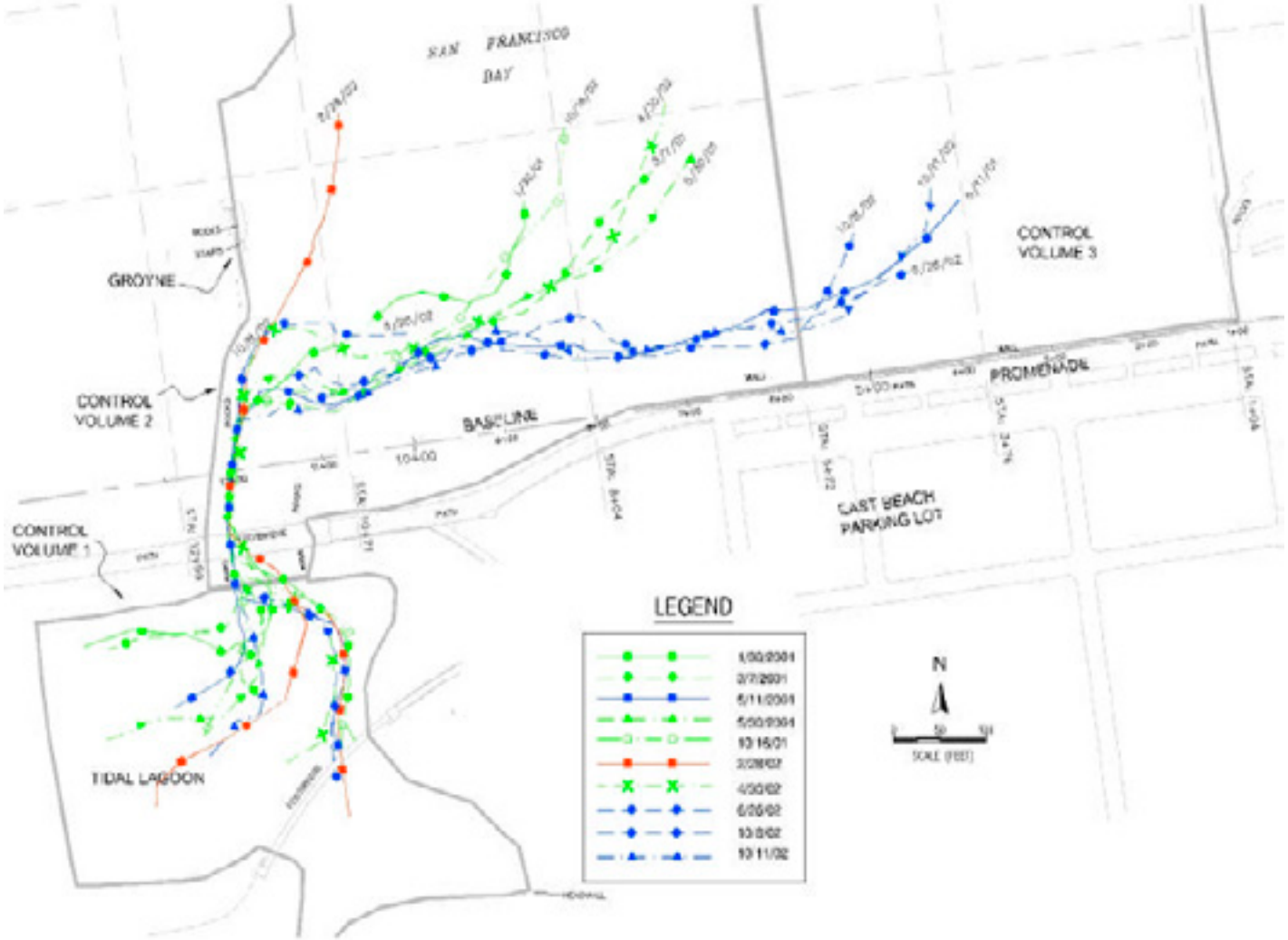
figure 4-4

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.

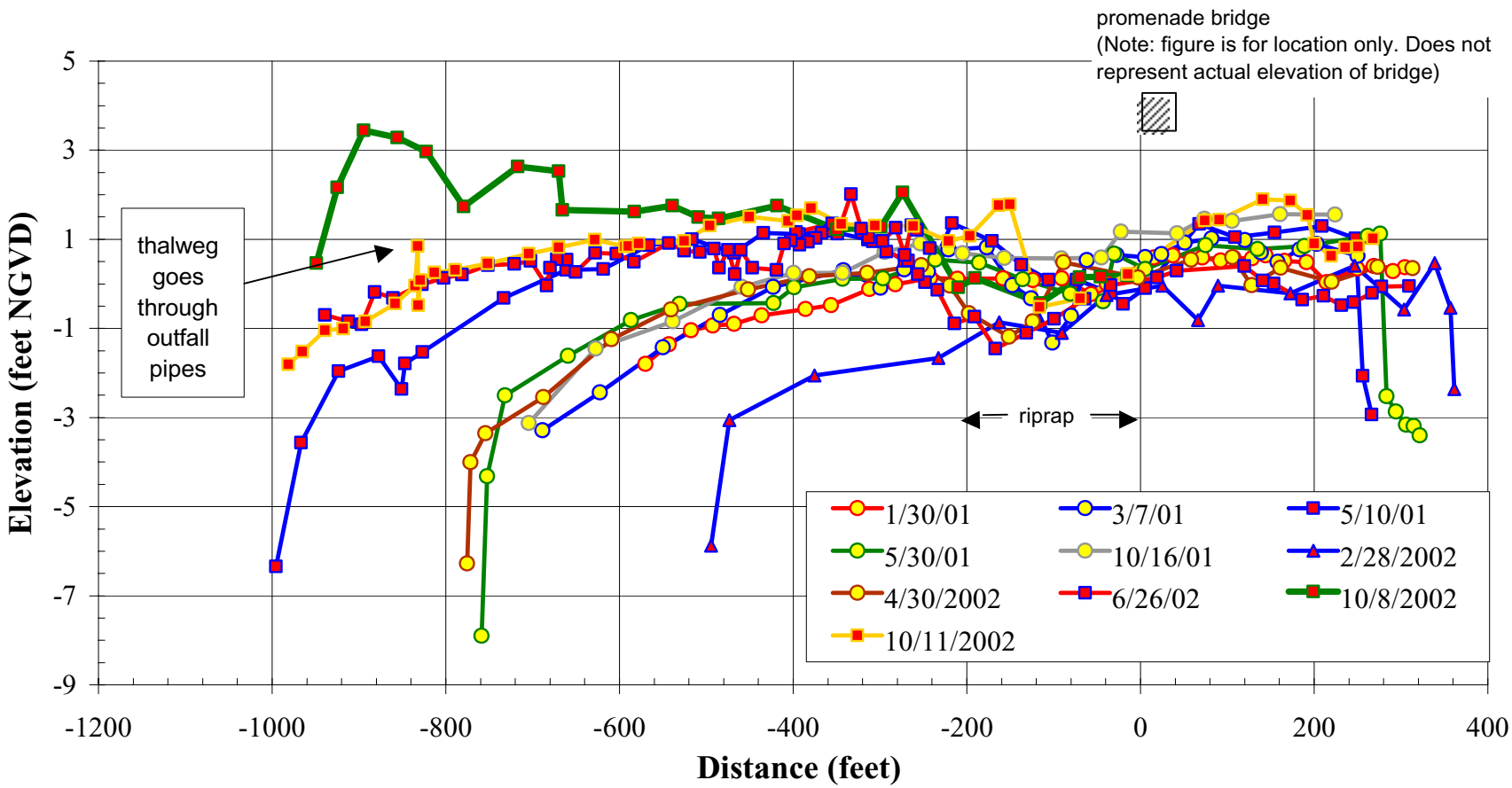
Source: PWA and GGNRA surrvey

figure 4-5

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

PWA#: 1623

PWA



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

Source: PWA and GGNRA surveys.

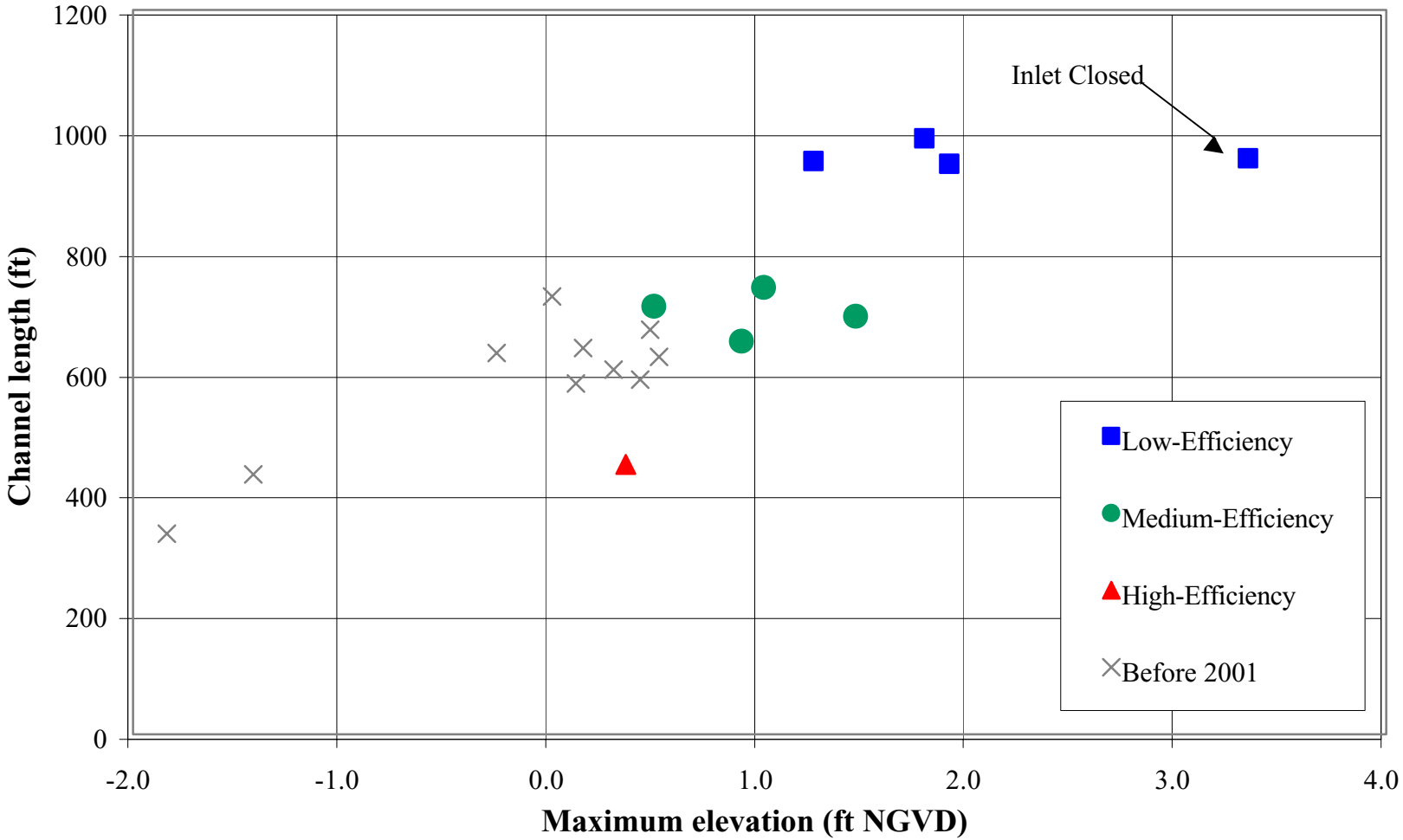
figure 4-6

Crissy Field Marsh Expansion Study

Entrance Channel Longitudinal Profile

PWA#: 1623

PWA



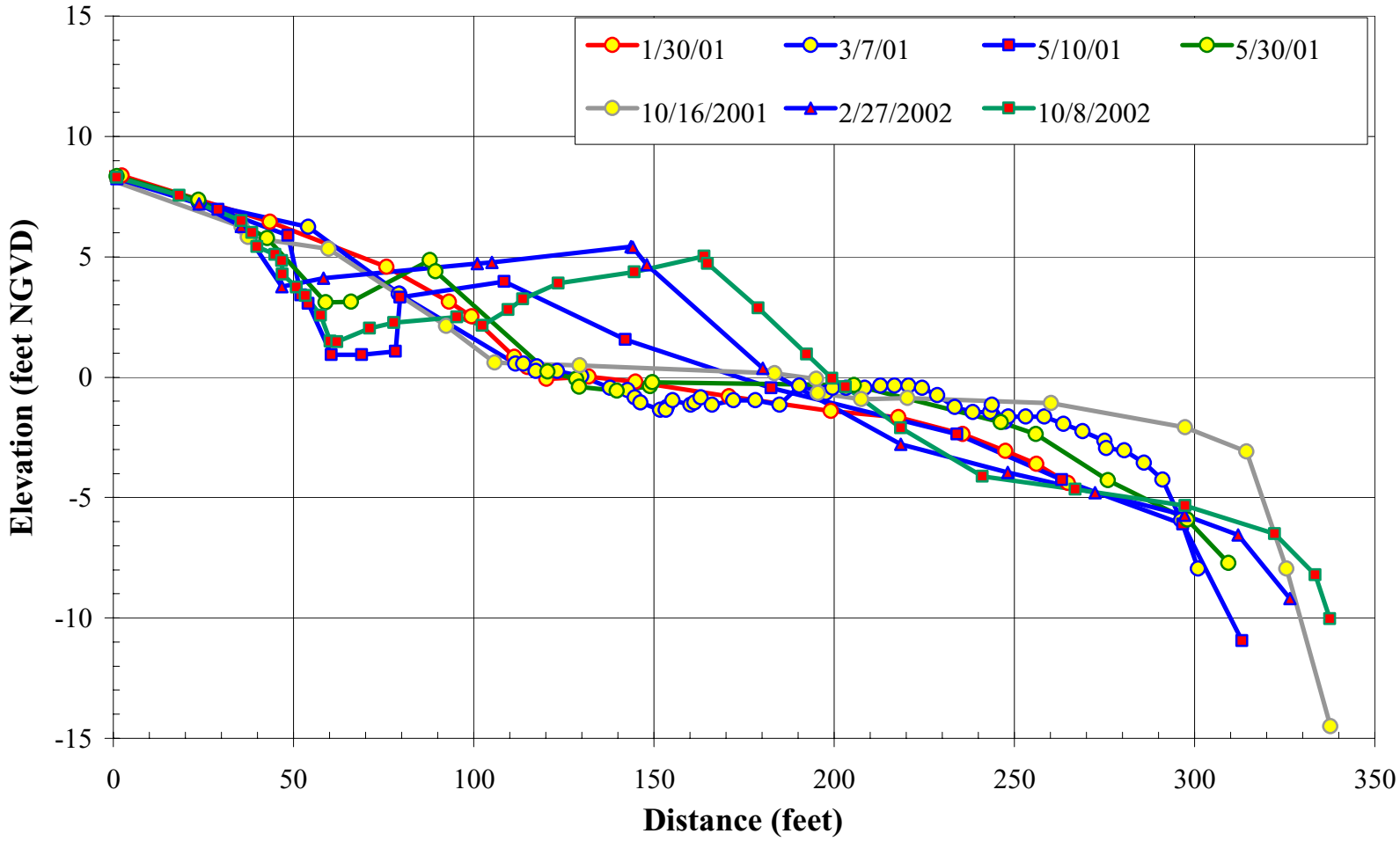
Notes
Source: PWA and GGRNA surveys.

figure 4-7

Crissy Field Marsh Expansion Study
Channel Length and Thawleg Elevation

PWA#: 1623

PWA



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

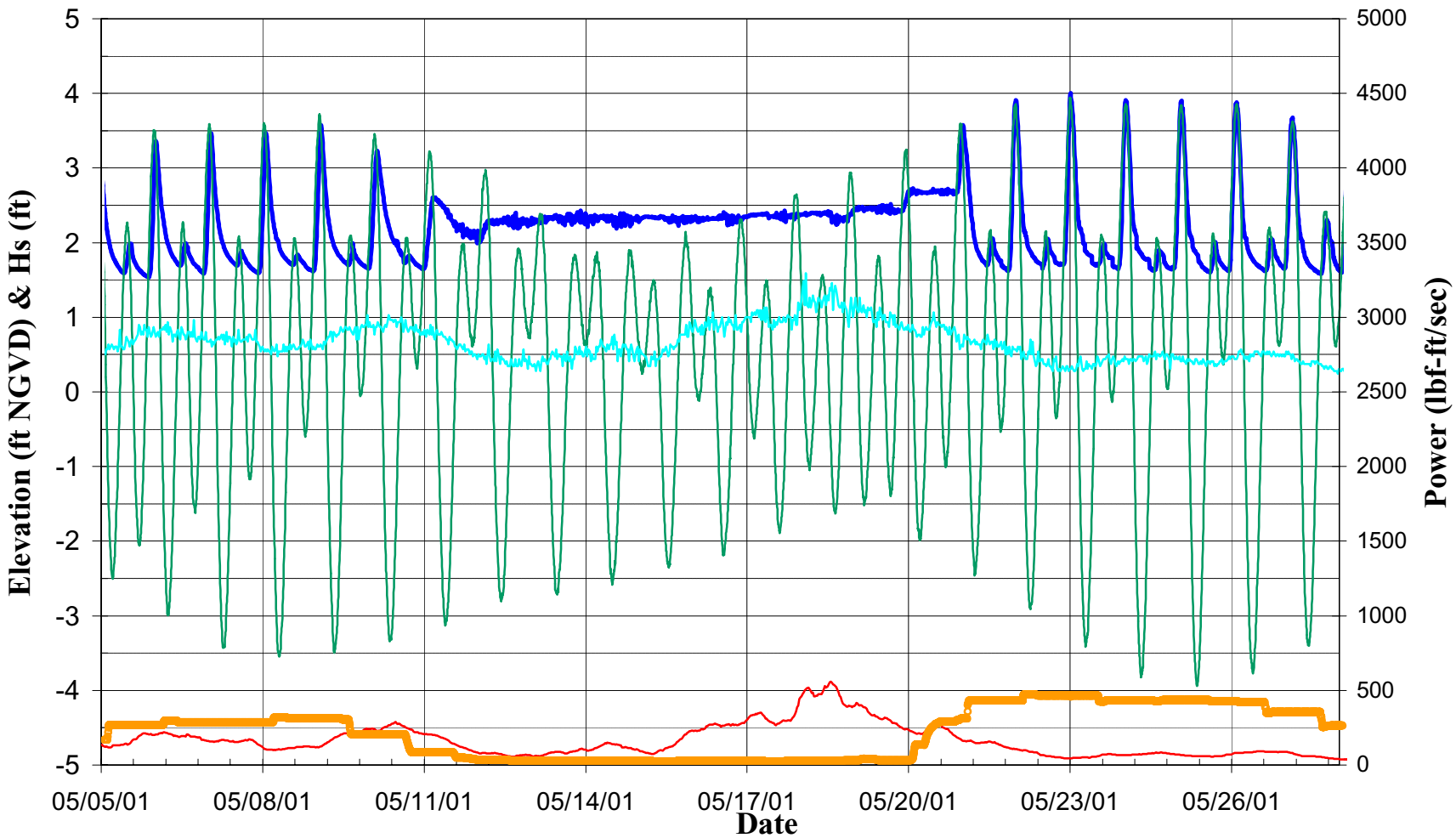
Source: PWA surveys.

figure 4-8

Crissy Field Marsh Expansion Study

Beach Profile 14E

PWA#: 1623



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.

- Crissy Tides
- Bay Tides
- Crissy Hs
- Crissy Wave Power
- Tidal Power

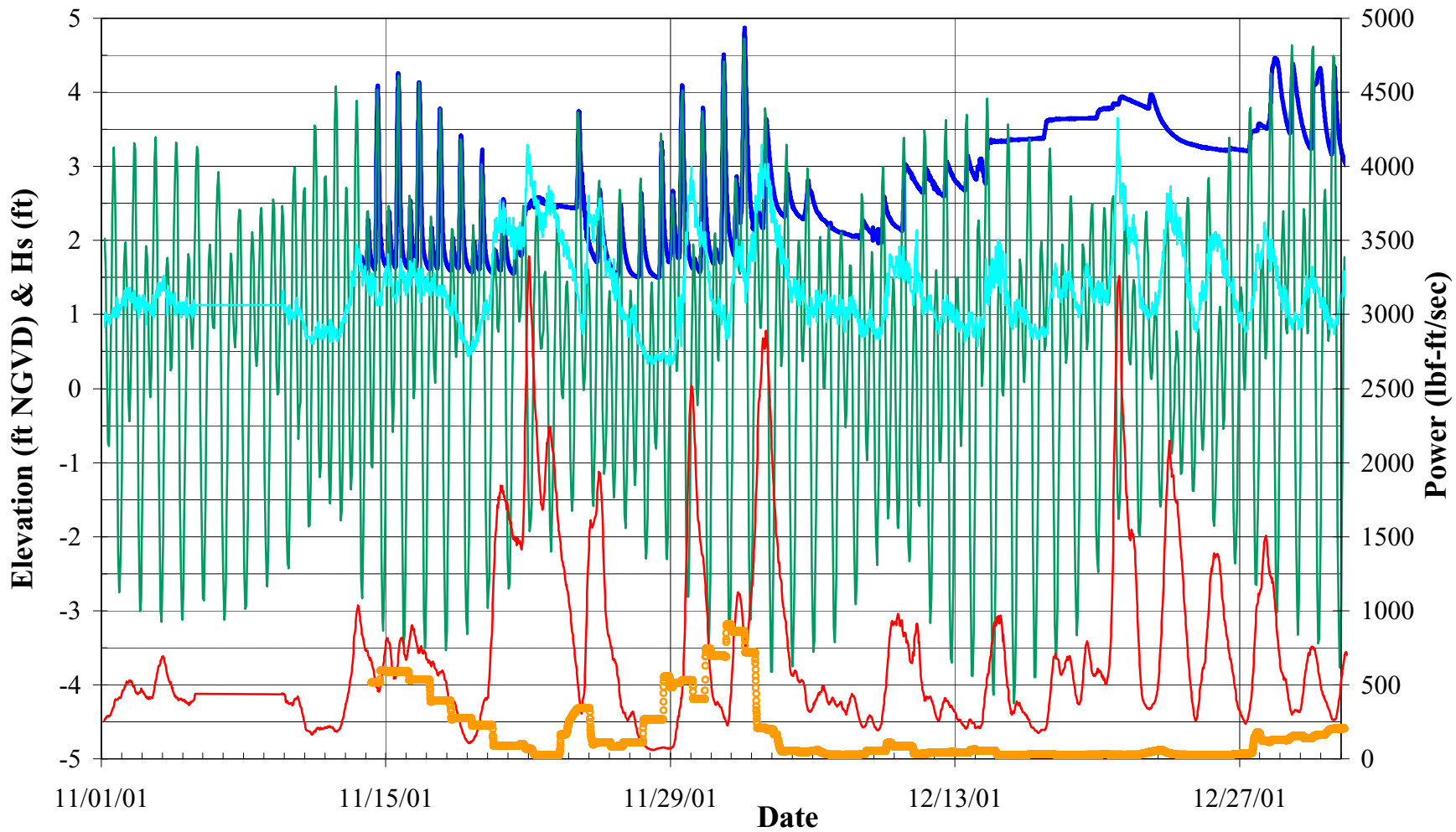
figure 4-9

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

PWA

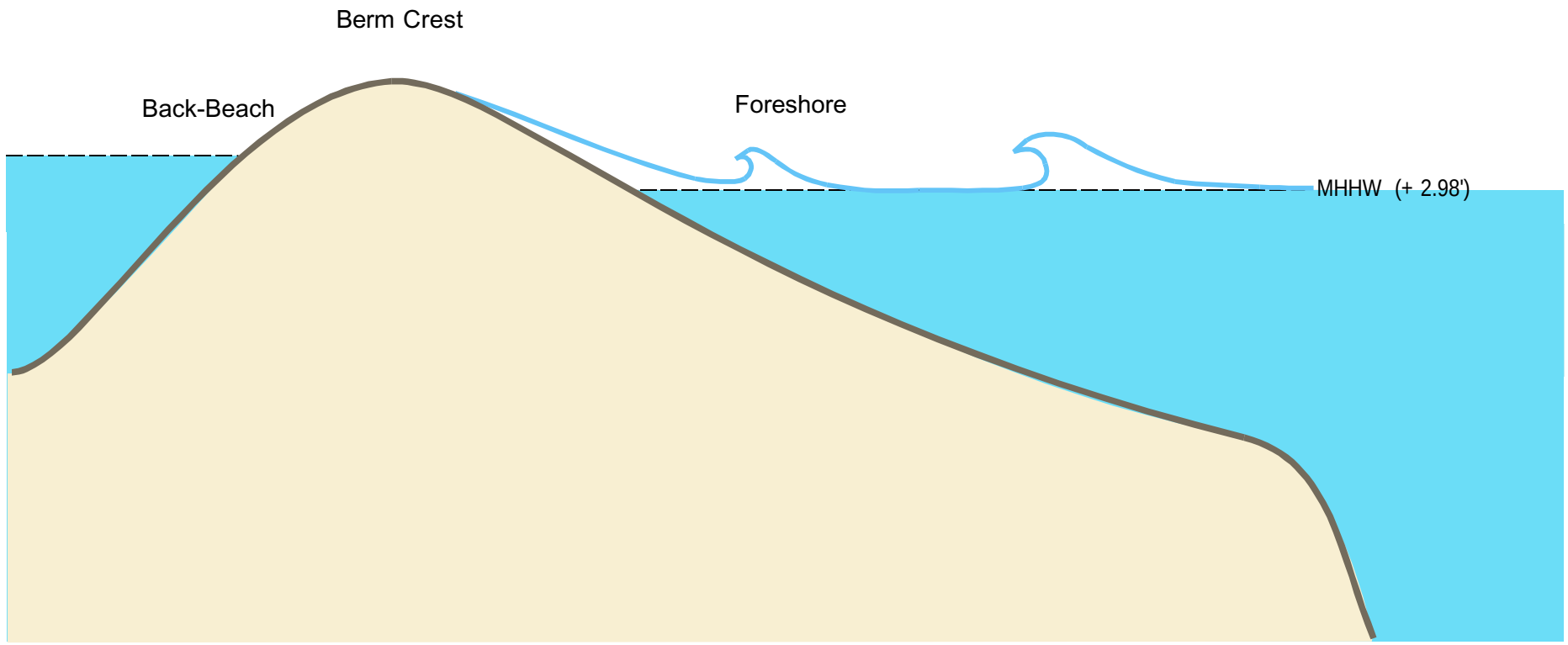


figure 4-11

Note: Not to Scale

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)

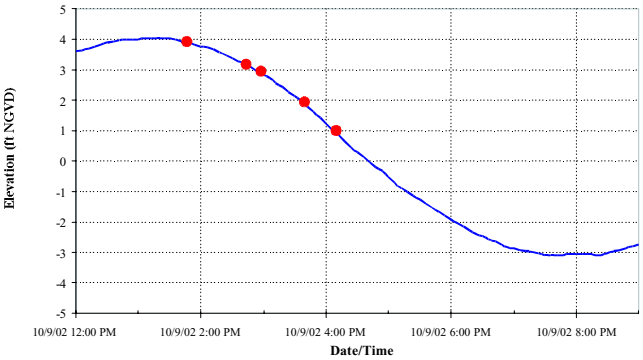

figure 4-12

Crissy Field Marsh Expansion Study

Breach of October 9, 2002

PWA

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figure 4-13

Crissy Field Marsh Expansion Study

Seepage Flow During Closure

PWA#: 1623

PWA

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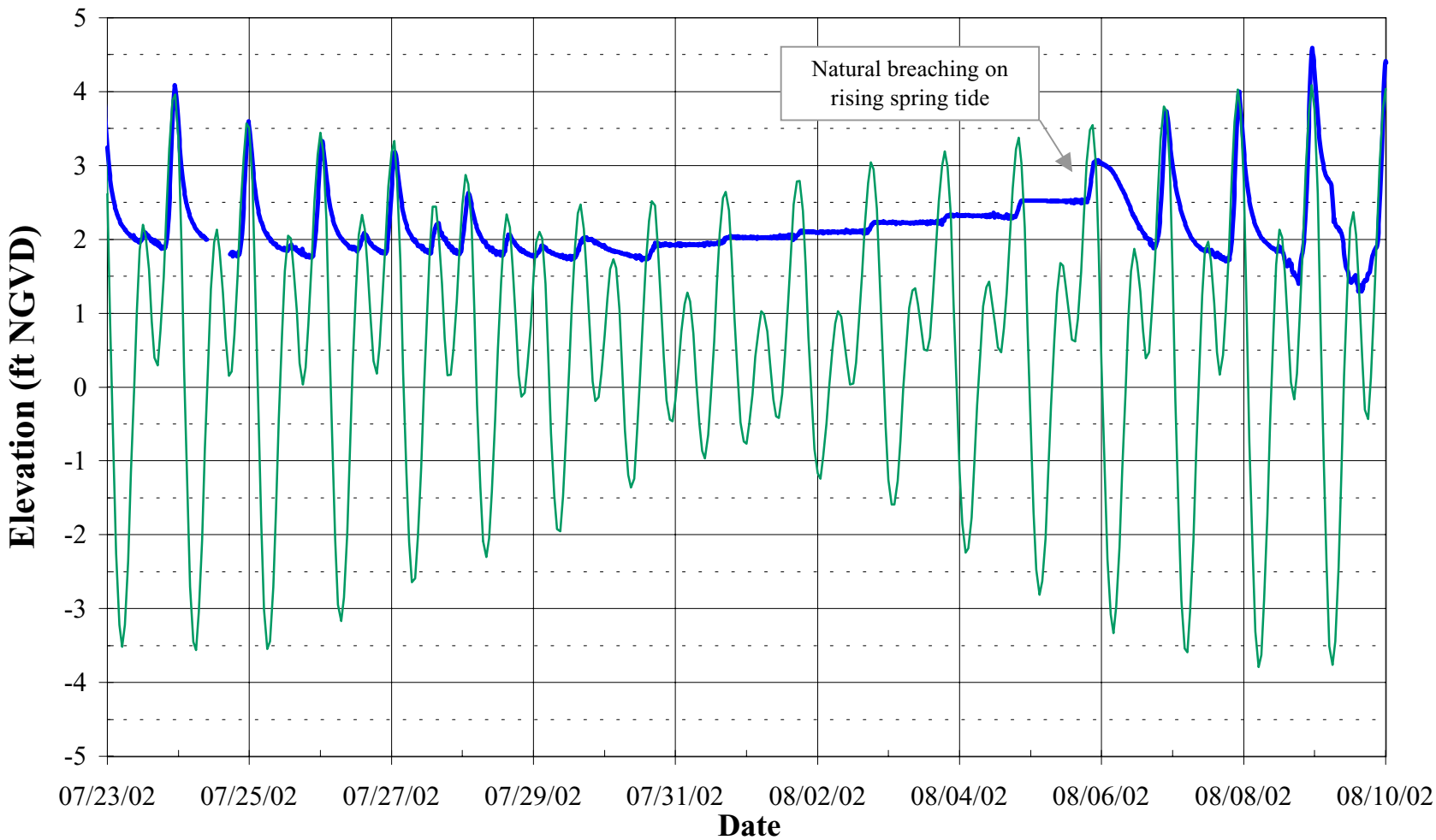

Source: Observed bay tides from NOAA/NOS station 9414290. Crissy tides from NPS.

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