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**Slough Channel Network and Marsh Plain Morphodynamics in a
Rapidly Accreting Tidal Marsh Restoration on
Diked, Subsided Baylands
San Francisco Estuary, California**

by

Stuart William Siegel

B.A. (University of California, Berkeley) 1986

B.S. (University of California, Berkeley) 1986

M.A. (University of California, Berkeley) 1993

A dissertation submitted in partial satisfaction of the

requirements for the degree of

**Doctor of Philosophy
in**

Geography

in the

GRADUATE DIVISION

of the

UNIVERSITY OF CALIFORNIA, BERKELEY

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**Slough Channel Network and Marsh Plain Morphodynamics in a
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Diked, Subsided Baylands
San Francisco Estuary, California**

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Stuart William Siegel

Abstract

**Slough Channel Network and Marsh Plain Morphodynamics in a
Rapidly Accreting Tidal Marsh Restoration on
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San Francisco Estuary, California**

by

Stuart William Siegel

Doctor of Philosophy in Geography

University of California, Berkeley

Professor David R. Stoddart, Chair

Since 1850, nearly 90% (about 60,000 hectares) of San Francisco Estuary tidal marshlands have been diked and drained for agriculture, salt production, waterfowl management, and development. Resource managers envision restoring 22,000 to 27,000 hectares of these “diked baylands” for natural resource conservation purposes. These lands have subsidence below marsh plain elevations, between 0.3-3m, presenting challenges for successful marsh restoration because tidal marsh elevations

must be restored to provide target ecological functions. When opened to the tides, these sites become intertidal “basins” with net accretion rates strongly influenced by incoming sediment concentrations, wind fetch, storms, tidal currents, runoff, salinity, existing site landforms, baseline elevations, consolidation, compaction, desiccation, and biomass accumulation.

Past restoration efforts have been mixed in meeting ecological goals, often due to channel networks inadequate to provide full circulation and elevations and substrate poorly suited for tidal marsh establishment. Resolving these problems is essential to meet the Estuary’s restoration goals.

This research examined temporal and spatial net sediment accretion patterns and the role of pilot channels and berms in controlling channel network evolution. This research used the Petaluma River Marsh restoration project, a 19-hectare diked bayland in the northwest corner of San Pablo Bay (subsided to local mean lower low water elevation) restored August 1994.

Small parallel berms spaced at 20m-intervals doubled channel density by promoting natural channel formation within the multiple small “watersheds” they create.

Confounding site factors limit evaluating 35m spacing effects. Berms oriented across high velocity flow paths erode and thus do not promote channel formation. Pilot channels maintained planform position even while accreting sediment throughout their length. Minimal lateral migration occurred.

Accretion before vegetation colonization created gradients sloped away from the levee breach, controlled by the inverse relationship between elevation and accretion rates, velocity drops inside the breach, and within-tide variability in suspended sediment concentration. Once accreted to the distal reaches, elevations leveled out about 0.2m below mean high water. Subsequent static elevations with continued net sediment influx require similar magnitudes of competing processes that raise versus lower elevations. Summer low-tide exposure coincides with greatest winds, sunlight, and temperature that maximize elevation-lowering desiccation and consolidation processes.

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Chapter 1.0 Introduction

In the San Francisco Estuary, California, resource managers currently envision 22,000 to 27,000 hectares (55,000 to 65,000 acres) of tidal marshland restoration for the primary purpose of natural resource recovery and conservation. This restoration would reverse much of the anthropogenically-caused losses over the past 150 years that removed about 150,000 ac (60,000 ha) of tidal marsh in the Estuary (Goals Project 1999). The lands on which a vast majority of this restoration can take place are former tidal marshlands, diked and drained for other land uses (primarily agriculture, salt production and waterfowl management) beginning in the late 19th century.

The most significant attribute of these restorable lands is their subsidence below marsh plain elevation. The magnitude of subsidence typically ranges between 0.3-3 m (1-10 ft) in the Estuary proper (Goals Project 1999), and between 3-8 m (10-25 ft) in the Sacramento-San Joaquin river delta that drains into the Estuary (DWR 1993).

Subsidence poses a large challenge for effective, sustainable and successful marsh restoration because tidal marsh elevations and geomorphic elements must be recreated, naturally and/or through human intervention, in order for tidal marsh ecological function to become established.

The purpose of the research presented in this dissertation is to contribute to our understanding of restoring tidal marsh ecosystems and thereby help to resolve some of the outstanding questions surrounding how to restore these natural ecosystems

successfully. This research contributes not only in examining a topic of great significance, tidal channel and marsh plain geomorphic evolution, but it provides a tremendous amount of very high-resolution data that can be used far beyond the work presented here.

This study focuses on a very specific landscape setting that is very common to the San Francisco Estuary and the potential tidal marsh restoration sites: subsided diked former tidal marshlands. When opened to the tides, these sites become intertidal “basins” subject to natural sediment deposition. Deposition rates are strongly influenced by incoming sediment concentrations, which in turn are influenced by a wide variety of extrinsic forcing functions (e.g., wind, storms, tidal currents, runoff, salinity), and by conditions within the restoration site (e.g., existing landforms, elevations, and wind fetch). The most ideal conditions from a restoration perspective typically are those that lead to the most rapid accretion, as they promote the most rapid recovery of ecological functions.

This research seeks to fill knowledge gaps described in later sections by carrying out two studies. The first study, presented in Chapter 5, examines temporal and spatial patterns of sediment accretion for help in understanding how a tidal marsh restoration site evolves overall and how that information may be useful in predicting geomorphic evolution at other restoration projects. The second study, presented in Chapter 6, examines the role of initial condition (i.e., use of pilot channels and berms) in controlling geomorphic evolution of the tidal channel network in particular. The site

selected for this research, the Petaluma River Marsh restoration project, is a 19-hectare (48-acre) diked former tidal marshland that had subsided to about local mean lower low water elevation and was restored to tidal action in August 1994. The site is located in the northwest corner of San Pablo Bay along the Petaluma River just upstream of its confluence with the bay (Map 1-1).

This dissertation is organized into six chapters plus references and data appendices:

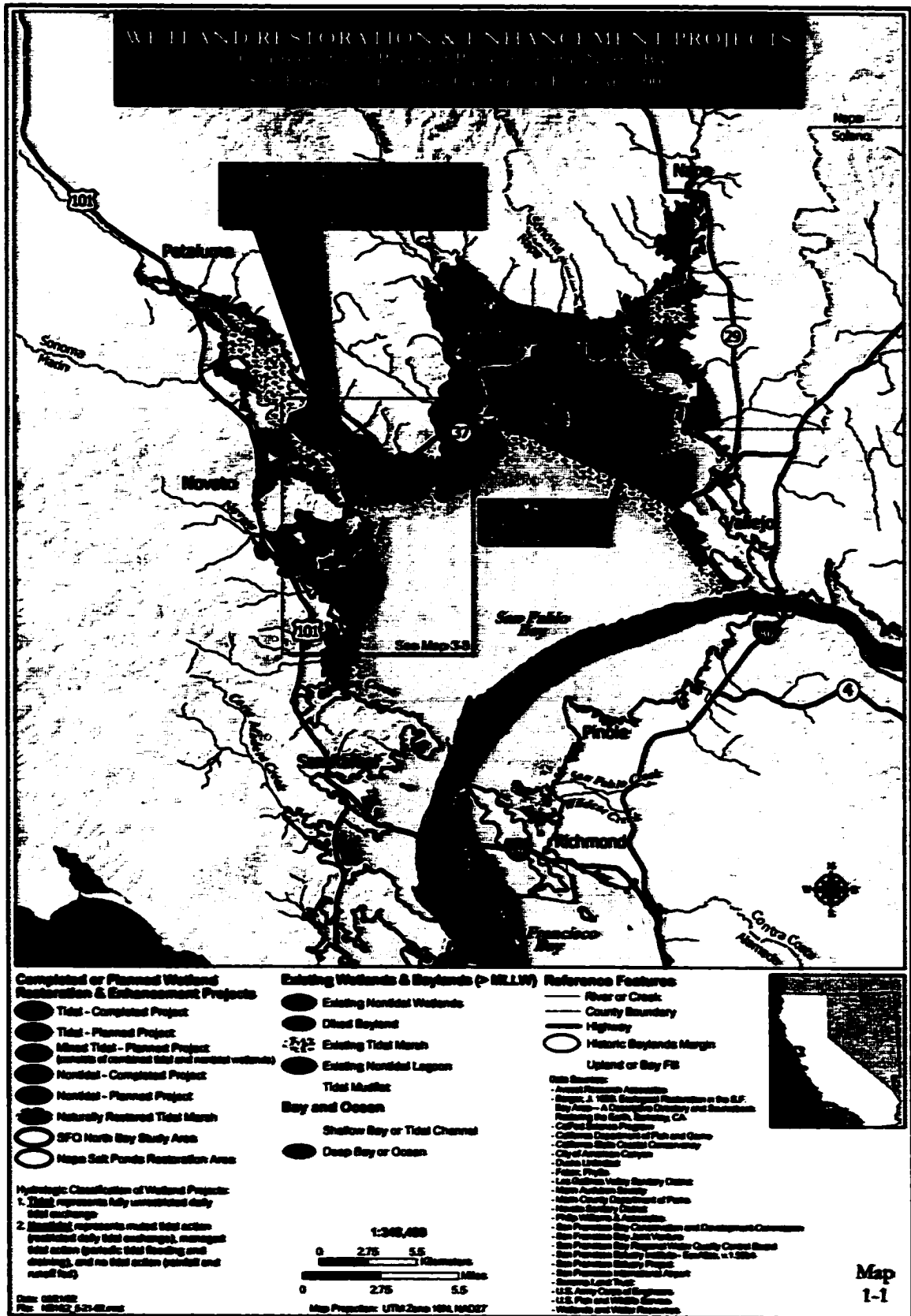
- Chapter 1: Introduction
- Chapter 2: Wetland Restoration Science Overview
- Chapter 3: Site Description and Restoration Design
- Chapter 4: Methods
- Chapter 5: Temporal and Spatial Accretion Patterns
- Chapter 6: Role of Initial Conditions
- References and Bibliography
- Appendix

1.1 Importance of Geomorphology and Tidal Channel Networks for Successful Tidal Marsh Restoration

Recent publications pertaining to the field of tidal marsh restoration ecology have emphasized that understanding geomorphic processes and how they shape wetland

ecology is essential to successful ecological restoration efforts. Though such a statement may seem trivial, previous efforts in tidal marsh restoration have suffered difficulties in part because such understanding was not built into the design process (French and Reed 2001, Callaway 2001, Mitsch and Gosselink 2000, Weinstein and Kreeger 2000). These works have stressed the significance of functioning tidal channel networks to the successful outcome of restoration efforts. Intertidal wetlands occupy a unique landscape position in which their elements of “land” emergent above the tides and “water” below the tides constantly change with the daily rise and fall of the tides. Tidal wetland ecology, therefore, closely tracks this dynamic physical setting (French and Reed 2001, Callaway 2001, Mitsch and Gosselink 2000, Zedler 2001, Weinstein and Kreeger 2000).

The slough channel network is critical to the success of any tidal marsh restoration project because of the two fundamental functions channels perform in tidal marshlands. First, tidal channels are the conduits through which water, sediment, nutrients, and aquatic organisms circulate into, around, and out of the marsh. This distributary function directly controls most of the physical conditions in a tidal marsh to which plants and wildlife are subject. In turn, this distributary function reflects the marsh geomorphology, tidal range, sediment loads, marsh substrate, and marsh vegetation. Consequently, channel morphology is a primary forcing function for ecology (Mitsch and Gosselink 2000, Weinstein and Kreeger 2000, Callaway 2001, French and Reed 2001).



Second, channels provide essential habitat for a wide variety of fish and wildlife species. Channels are edge habitat for species such as the endangered California Clapper Rail, a bird that nests and feeds along cordgrass vegetated channel banks (Albertson and Evens 2000). Channels are shallow water habitat for dabbling and diving ducks (Takekawa *et al.* 2000). Channels are forage habitat and ingress/egress routes for a wide variety of fish species and previous researchers have attributed population size reductions to the tremendous loss of tidal marsh habitat in the San Francisco Estuary in the late 19th century (Bennett and Moyle 1996).

Marsh plains are the structural basis of vegetated tidal marshlands and the habitat for much tidal marsh fauna (Teal and Teal 1969, Nixon 1980, Josselyn 1983, Weinstein and Kreeger 2000, Callaway 2001, French and Reed 2001). How marsh plains evolve thus is a critical component in predicting the outcome of marsh restoration efforts. Marsh plain evolution integrates physical processes such as sediment accretion (including processes that raise and lower absolute ground surface elevations) and biological processes such as vegetation colonization, burrowing invertebrate organisms, probing birds, and surface-foraging fish species. Restoration projects are often interested in predicting the temporal and spatial evolution of the marsh plain (e.g., CSCC and USACE 1998) to establish anticipated temporal sequence of ecological function re-establishment and to make determinations regarding whether elevation modifications (e.g., dredged sediment placement) should be incorporated into project design.

1.2 Shortcomings of Past Restoration Efforts

Shortcomings of past restoration projects have been identified in many cases to stem from a channel network that is inadequate to provide these two essential functions and marsh plain elevations and substrate quality poorly suited for tidal marsh establishment (Race 1985, Goals Project 1999, French and Reed 2001, Callaway 2001). Improving our ability to restore functioning tidal slough channel networks and to recreate appropriate marsh plain elevations and substrate is critical to achieving the magnitude of restoration envisioned for the San Francisco Estuary (French and Reed 2001, Callaway 2001). Previous problems include undersized levee breaches, inability of natural processes to scour channels in existing (or newly placed) substrate, insufficient channel network development, restricted tidal exchange between the site and the nearby open tidal waters, low rates of sediment accretion and thus slowly evolving ecological functions, unanticipated scouring of enclosing levees, low channel density, no small channels, low sinuosity, no steep-sloped channel banks, poor channel bank stability, insufficient emphasis on intertidal versus subtidal channels, improper topography along channel – mudflat/marsh plain edges to facilitate overbank flooding, too high of elevations, acid sulfate soil chemistry, and too coarse of sediment grain size for proper nutrient uptake chemistry (Goals Project 1999, French and Reed 2001, Callaway 2001, personal observation).

1.3 Key Attributes of Potential San Francisco Estuary Tidal Marsh Restoration Sites

In the San Francisco Estuary, sites with potential for restoration to tidal marsh are largely diked baylands with land uses that fall into the following categories: farmed (e.g., much of San Pablo and Delta sites), salt pond (Napa River, South Bay), managed wetlands (primarily Suisun), and unmanaged wetland (“abandoned” diked wetland relatively common along the southern Suisun Bay shoreline). Each of these categories, in turn, creates common sets of physical and biological characteristics that influence the ecological outcome of restoration efforts. Important physical characteristics include degree of subsidence (amount of sedimentation needed, whether elevations and initial substrate conditions suitable for plant colonization exist at the outset), distance from and constraints on tidal source (ability to obtain unrestricted tidal exchange), exposure to long wind fetches (sediment resuspension), sediment supply (sedimentation rates), soil salinity and contaminants (substrate suitability), adjacent land use (e.g., island versus upland, streams for surface and subsurface freshwater inputs, undeveloped versus developed upland edge), and infrastructure constraints. Important biological characteristics include possible seed banks, existing vegetation, proximity to other wetlands (propagule sources), displacement of biological resources, adjacent land use (wetland-upland transition potential), and structural diversity (habitat availability). The most important of these attributes are shown in Table 1-1.

Table 1-1. Characteristics of Initial Conditions at Potential Restoration Sites in the San Francisco Estuary and Sacramento-San Joaquin Delta

Initial Condition	Regions of Occurrence	Degree of Subsidence	Geomorphic Heterogeneity	Existing Plants for Revegetation	Substrate Suitability for Revegetation
Farm	San Pablo Bay, Delta	Usually considerable	Usually converted to drainage ditches, some swales	None; if exists, typically will be buried	No concern
Salt pond	San Pablo Bay, South Bay	Usually little	Often preserved channel networks; depressions may be common	None	Potentially major concern
Managed wetland	Suisun Bay, some San Pablo and South Bay	Usually little	Varies; either converted to drainage ditches with some swales or preserved channel network and broad depressions	Some; controlled species composition	Could pose concern
Unmanaged wetland	Suisun Bay, some San Pablo and South Bay	Varies depending on prior land uses	Highly variable depending on prior land uses	Some; varied species composition; buried at deeply subsided site; important at minimally subsided sites	Could pose concern

General marsh evolution derives from four fundamental forcing functions, which vary in their internal (site) versus external (estuarine) origins:

- **Inundation** is controlled by site topography (internal), tidal range (external), and degree of tidal restriction (mixture of internal and external).
- **Surface water salinity** is controlled by climate and water use (external).

- **Sediment supply** is controlled by many factors, including proximity of mudflats, wind regimes, proximity of watershed and Delta outflow inputs, and morphology of tidal connection (external).
- **Substrate characteristics** are defined by a combination of physical, chemical, and biological processes at different stages. Prior to restoration, site history defines subsidence, hydrology, vegetation, soils, and land use. Restoration construction can include grading, compaction, conditioning, dredged sediment placement, planting, and the like. Once tidal, net accretion is controlled by processes that raise site elevations (sediment deposition from tides and storms, biomass production) and lower elevations (sea level rise, decomposition, consolidation, compaction, desiccation, erosion).

Forcing functions that originate from within the site offer the potential for engineering design of the initial conditions to promote achieving the desired restoration outcome.

Forcing functions that originate from outside the site offer less engineering design potential but to varying degrees can, through engineering design, be guided to promote desired ecological outcomes.

1.4 Existing Channel Design Guidance

Few hydrologic design guidance documents exist for restoration practitioners. The U.S. Army Corps of Engineers Waterways Experiment Station commissioned

preparation of one such document (Coats *et al.* 1995) that has been referenced in subsequent technical documents. For channel cross sectional geometry, that design guidance document relies upon hydraulic geometry relationships derived from a limited data set and it uses a tidal prism (volume of tidal waters) of mean lower low water to mean higher high water as the dominant discharge. For channel planform geometry, that document presents a very broad range of morphological characteristics (channel order, channel linear density, bifurcation ratio, sinuosity) that exhibit large variability and thus do not provide much insight into quantitative attributes of natural wetland channel networks. Lack of more advanced technical guidance documents has led to the propagation of that approach around the United States (e.g., Zeff 1999, Weinstein *et al.* 2000).

Hydraulic geometry has an inherent appeal for restoration design, as it can provide a simple tool for relating tidal prism to channel geometry. Its underlying premise is that there exists a “dominant discharge” responsible for most of the geomorphic work that shapes channel geometry (Leopold and Maddock 1953). However, its valid extension from fluvial to tidal systems is not clearly established. The primary unknown is whether a geomorphically dominant discharge exists in tidal systems and, if it does, defining that event (Leopold *et al.* 1993, Siegel 1993, Siegel and Wells 1994, French and Reed 2001).

One earlier design guidance document (Collins 1991) provided a more detailed approach to channel geometry based on extensive data from a small number of

locations. The author has been involved in projects applying that guidance and it has become clear that regional variations in estuarine forcing functions (e.g., tide range) limit its application without further elaboration.

Finally, some restoration practitioners have followed a straight civil engineering fluid mechanics approach (e.g., Johnson *et al.* 1994). In this method, they estimate tidal prism by one of several methods, convert these volumes into a discharge value based on duration of a tidal cycle (which generates some form of an “average” or “representative” tidal discharge), then apply the Manning’s equation to derive channel geometry. This approach may have some utility but relies on some user-selected representative tide and friction values derived empirically from sources generally outside tidal marsh systems.

1.5 Restoration Strategies for San Francisco Estuary Diked Subsided Baylands

Restoring Elevations

In the San Francisco Estuary, two general strategies are employed to restore diked baylands to tidal marsh: the “natural sedimentation” approach and the “dredged sediment reuse” approach. Natural sedimentation relies upon natural processes of sediment accretion to raise site elevations to that suitable for plants and wildlife to colonize and use the site. Dredged sediment reuse replaces part of these natural

processes with mechanical placement of sediments dredged from elsewhere within the San Francisco Estuary. Typically, dredged sediment is placed to elevations somewhat below local mean high water (MHW) so that natural sedimentation can provide the surface layer of sediment into which plants and animals predominantly colonize and so that placed dredged sediment does not hinder scouring and channel formation (Goals Project 1999). Dredged sediment reuse is generally considered only where sites have undergone considerable subsidence (e.g., typically >2m (6ft)).

Restoring Channels

Multiple strategies for restoring channels within tidal marsh restoration projects exist and which to apply depends upon initial geomorphic and substrate conditions and economic considerations. Where considerable subsidence has occurred and the natural sedimentation restoration strategy is employed, channels are anticipated to form naturally within the accreting sediments and small pilot channels might be helpful to promote that formation. This approach describes the strategy employed at the Petaluma River Marsh, the subject of this research.

At subsided sites to be restored with dredged sediment reuse, multiple strategies exist only one of which has been attempted in the San Francisco Estuary. The strategy used so far is to fill the site with sediment and allow for erosion to scour out a channel network concurrent with accretion of the adjacent marsh surface. Fill elevations are critical and earlier restoration projects in the region (e.g., Muzzi Marsh in Marin County, Faber Tract in Santa Clara County, and Pond 3 in Alameda County) have

shown an inverse relationship between scour potential and initial fill elevations (Goals Project 1999). These earlier problems have led to recommendations for dredged sediment to be placed no higher than somewhat below local MHW and allowing for natural sedimentation to provide the final accretion to resolve the problem of poor channel formation. An alternative strategy designed into the Montezuma and Hamilton projects but not yet implemented is to construct “cells” within the site with levees and to separate these cells with areas that will not receive sediment placement, effectively leaving a “channel” behind.

At sites with relatively little subsidence, channels can be restored in one of three ways. Channels could form through erosion of the existing ground surface, the success of which depends upon the erosion potential of site soils. Alternatively, mechanical excavation of channels can be employed, as has been done at the Martin Luther King, Jr. marsh restoration project in Oakland (WWR 2002a) and the Oro Loma marsh restoration project in Hayward (WWR 2002b). Finally, at site with intact antecedent channel networks (limited primarily to some salt ponds), little or no work may be necessary except perhaps to close off levee-parallel borrow ditches (Orr *et al.* 2001, Siegel and Bachand 2002).

1.6 Study 1: Temporal and Spatial Patterns of Accretion

Sediment accretion is the physical process component responsible for building substrate suitable for tidal marsh flora and fauna to colonize and thereby contribute to subsequent accretion. Understanding how natural sediment accretion processes build that marsh plain over time and spatially across a restoration site provides a crucial piece of data for predicting these processes at other restoration sites. Such predictions are often done with sophisticated computer models incorporating hydrodynamics and sediment supply (e.g., Falconer and Owens 1990; Falconer and Chen 1991; Chen and Falconer 1992; Lin and Falconer 1995, 1996, 1997a, and 1997b).

Sediment accretion onto a restored diked bayland is a vertical topographic change. Natural marshes formed during sea level rise laterally flooding river valleys and during periods of high sediment loading laterally encroaching into intertidal mudflats. This vertical to horizontal accretion difference defines a new mode of marsh formation not explicitly accounted for by those modes. The link between elevation and vegetation colonization demarcates a significant biological transition, as vegetation introduces habitats and biomass production, promotes deposition, and shields the ground from sun and wind exposure, all of which raise site elevations (Redfield 1964 and 1972; Mahall and Park 1976c; Atwater *et al* 1979; Nixon 1980; Josselyn 1983; Turner *et al.* 2000).

The general question regarding geomorphic evolution is the following:

- *What are the spatial and temporal patterns of net sediment accretion in a flooded tidal basin restored to tidal action for the purpose of re-establishing tidal marsh?*

The specific research questions that derive from this general question and that are examined in this research (see results and discussion in Chapter 5) are the following:

- *How do net sediment accretion rates vary over time?*
- *How do net sediment accretion rates vary as a function of elevation?*
- *What are the temporal and spatial patterns of net sediment accretion?*
- *What processes account for varying temporal and spatial patterns of net sediment accretion?*

To address these questions, I combined two approaches. I calculated per-tide net sediment mass influx values from the time series water level and suspended sediment concentration and DEM-derived volume hypsographs and compared those results to other time series data (high tide heights, etc.). I compared DEM elevations between years to examine temporal and spatial patterns of net sediment accretion.

1.7 Study 2: Role of Initial Conditions

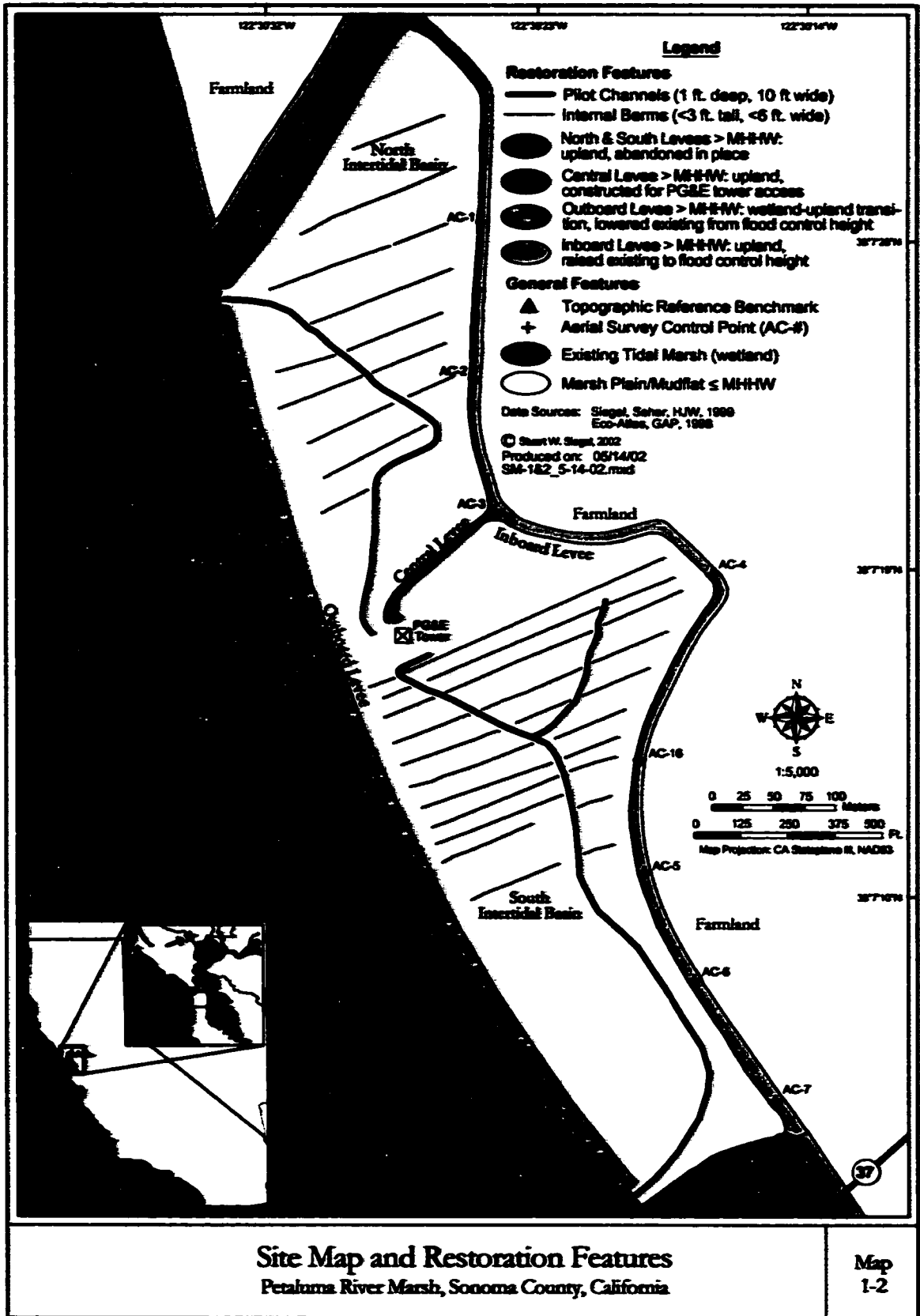
The field observation at the Petaluma River Marsh Restoration Site (Map 1-2; see description in Chapter 3) is that, despite complete burial from naturally deposited sediment, initial conditions created during project construction have strongly influenced geomorphic outcome. These initial conditions included pilot channels (intentional) and small parallel berms (incidental to construction). See Chapter 3 for a description of the restoration design and construction for the study site.

The general question that emerges from this field observation is the following:

- *How can we maximize effectiveness of human intervention in achieving desired ecological outcomes in tidal marsh restoration efforts in the San Francisco Estuary on diked, subsided baylands?*

The specific research questions that derive from this general question and that are examined in this research (see results and discussion in Chapter 5) are the following:

- *In what ways have the pilot channels influenced channel morphology in planform, cross section, and network attributes?*
- *In what ways have the small parallel berms influenced natural channel formation?*



Site Map and Restoration Features
Petaluma River Marsh, Sonoma County, California

Map
1-2

- *What conditions including pilot channels and small berms influence the minimal extent of lateral migration observed at the study site?*

At the Petaluma River Marsh in southern Sonoma County, California (Map 1-2), the restoration project included two significant initial conditions. First, small pilot channels (0.3m (1ft) deep and 3m (10ft) wide) were intentionally constructed to promote formation of a channel network. Second, numerous small internal berms (1m (3ft) tall and 2m (6ft) wide) were incidentally constructed parallel to one another across part but not all of the site. These berms consisted of vegetation and surface soils scraped from the ground surface in advance of obtaining borrow soils needed for levee improvements. Berm spacing varied between 15-25 m (50-85 ft) in the southern basin and 25-45 m (85-150 ft) in the northern basin. All these features are now completely buried under naturally deposited sediment. To what extent have these two relatively minor features dictated geomorphic outcome of the channel network?

To evaluate these questions, I combined stereo-pair aerial photographs taken at three time intervals following restoration (2.6, 4.1 and 5.0 years) to generate orthorectified photographs and digital elevation models. I extracted several attributes of the channel network morphology from the orthophotos and digital elevation models. This study evaluates four parameters of channel morphology that are indicators of role of initial condition:

1. **Planform distribution relative to pilot channels:** determine how the channel planform morphology had evolved in relation to the pilot channels, which evaluates whether and to what extent the channels have migrated laterally away from the initial template.
2. **Elevation relative to pilot channels:** determine how channel cross sectional and longitudinal profiles grew from the initial conditions, which evaluates the significance of pilot channel geometry in affecting resultant channel geometry.
3. **Planform distribution of channels relative to the berms:** determine the quantitative attributes of natural channel formation between and away from the small, parallel berms, which informs the extent to which these berms influenced natural channel formation.
4. **Network relative to pilot channels and berms:** determine how the channel network attributes change over time, which evaluates the extent to which initial conditions affected where network change occurred in response to the feedback between evolving geomorphology, hydrologic regime, sediment supply, and desiccation.

Since vegetation colonization had barely started at the conclusion of the research, its role in controlling channel morphology could be ruled out.

Chapter 2.0 Wetland Restoration in the San Francisco Estuary

This chapters reviews a number of topics germane to the field of wetland restoration science and the specific application of that science to this research effort. Estuarine tidal marsh restoration is a relatively new human activity, extending back about three decades in the San Francisco Estuary and of similar time periods elsewhere globally. Consequently, the recent literature contains a number of very informative volumes that will be referenced in this chapter.

The most basic issue facing wetland restoration, regardless of wetland type, is achieving successful outcomes. The body of literature examining evolutionary trajectories in restored estuarine tidal marshlands around the world raises one dominant message: evolution responds to a complex continuum of conditions that derive from baseline site conditions (e.g., degree of subsidence relative to modern sea level, extent of vegetation, soil chemistry, and hydrology, all of which extent from recent land use history), restoration design details (e.g., extent of engineered alterations and allowance for natural geomorphic and biological processes), and landscape setting (e.g., extent of tidal restrictions, types of adjacent land uses and resultant edge character, tidal range, degree and timing of freshwater inputs, salinity regimes, suspended sediment concentrations, grain sizes, proximity to other tidal marshes as colonist sources).

The following discussions pertinent to wetland restoration science are organized into seven sections:

- **Section 2.1 describes tides in the San Francisco Estuary**
- **Section 2.2 summarizes sediment desiccation processes**
- **Section 2.3 discusses sediment supply and transport**
- **Section 2.4 examines tidal marsh restoration issues**
- **Section 2.5 addresses channel formation processes**

2.1 Tides of the San Francisco Estuary

The dominant physical forcing functions in tidal wetland ecology and restoration include tidal range, tide type, freshwater inflows, and sediment regime (French and Reed 2001). In comparing and contrasting this study site to other tidal wetland restoration efforts within the San Francisco Estuary and elsewhere around the world, it is important to know the applicable tidal regime.

2.1.1 Tide Types and Range

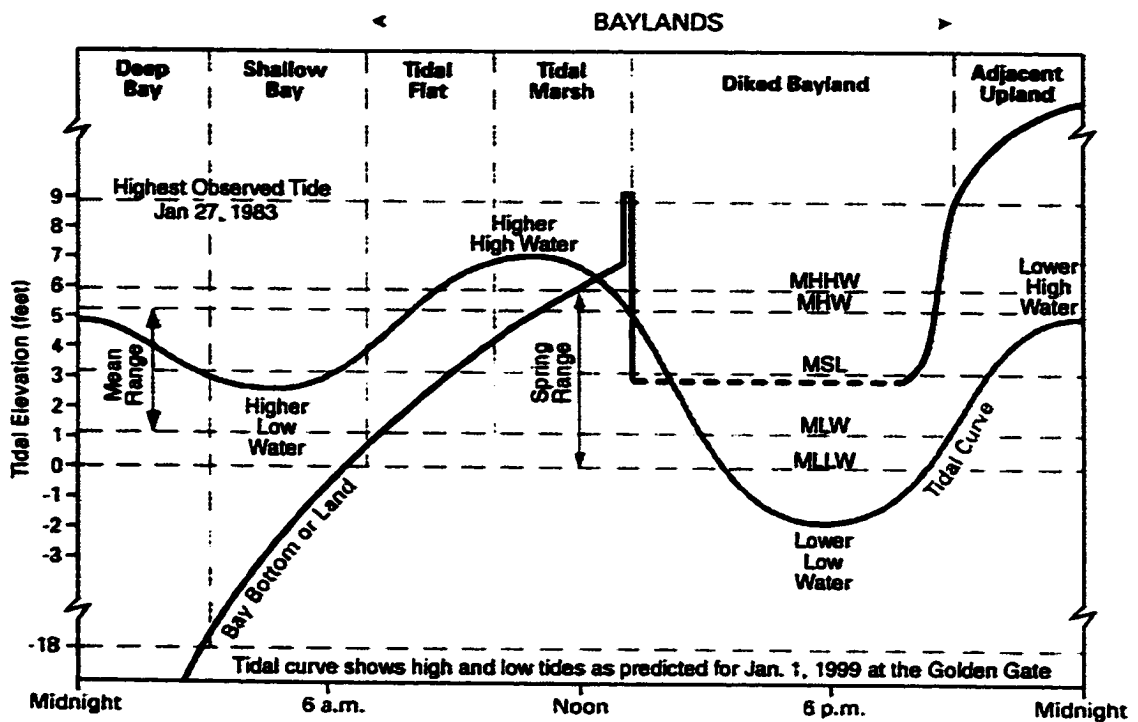
One of the most fundamental forcing functions in tidal marshes worldwide is the tidal regime. Globally tides are described by their characteristics of frequency of high and low tides (daily or diurnal and twice-daily or semidiurnal) and whether the heights of

sequential highs (and lows) are variable (mixed) (Cartwright 1999). Tidal range is controlled by a complex combination of solar and lunar positions, large-scale oceanographic position, and local bathymetry.

The San Francisco Estuary experiences mixed, semidiurnal tides of meso-tidal range. The higher of the two high tides is referred to as the higher high tide, and the lower of the two high tides is referred to as the lower high tide (Cartwright 1999, Gill and Schultz 2001). Figure 2-1 shows the tidal datums applicable to the San Francisco Estuary.

Spring tide range at the Golden Gate, through which every tide enters and exits the estuary, is 1.78 m (5.83 ft) (NOS 1996). Once inside the Golden Gate, tide range varies along each of the two main estuarine axes (South Bay and North Bay/Suisun/Delta). The South Bay experiences tidal amplification and an oscillating standing wave due in large part to bathymetric influences (Conomos *et al.* 1985). Tide ranges in the South Bay reach 2.8 m (9.3 ft) (NOS 1983). The North Bay experiences more complex interactions of bathymetry and freshwater runoff from Central California. In general, tide range diminishes and mean sea level increases toward the Sacramento/San Joaquin River Delta and the tidal wave propagates as a nearly progressive wave (Conomos *et al.* 1985). Figure 2-2 illustrates this geographic pattern.

Figure 2-1. San Francisco Estuary Tidal Regime

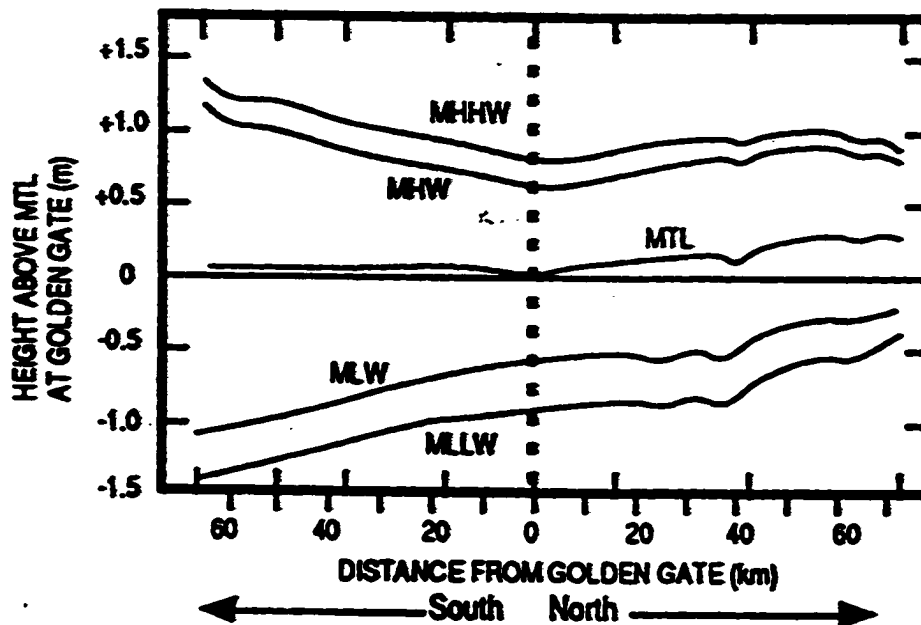


This schematic diagram shows tidal datums for the mixed, semi-diurnal tidal regime of the San Francisco Estuary as applied to the major baylands and adjacent habitats. The tidal curve and datums represent the Golden Gate. Bay bottom and land elevations are much more variable than shown, and the heights of the tidal datums vary around the Estuary.

Source: Adapted from Goals Project (1999)

Tide range in the vicinity of the study site is 1.85 m (6.06 ft) (NOS 1981) and mean tide level is 0.025 m (0.08 ft) higher than at the Golden Gate. Further east into Suisun Bay, tide range at Port Chicago is 1.48 m (4.86 ft) (NOS 2000). In addition, many of the larger local rivers and streams that discharge directly into the estuary experience tidal amplification a short distance upstream from their respective confluences with open water followed by reduced tidal ranges further upstream (Malamud-Roam 2000, comparison of NOS data for spatially distributed secondary tidal stations).

Figure 2-2. Tidal Range Variation within the San Francisco Estuary



South of the Golden Gate, the estuary is an enclosed, shallow basin that creates tidal amplification. North of the Golden Gate, the estuary transitions into the delta of the Sacramento and San Joaquin rivers and thus experiences tidal dampening and raised heights of the tidal datum.

Source: Josselyn 1983

2.1.2 Influence of Runoff from Local Watersheds and Central Valley

Tide levels are also affected by climate through storm-generated runoff and to a much lesser degree through spring snow melt in the Sierra Nevada. Local watersheds can contribute significant peak storm flows and these effects would be strongest at the mouths of the watershed. Runoff from interior Central California is of a far greater magnitude, as the watershed comprises 40% of the State of California and encompasses the orographic effect of the Sierra Nevada mountain range and its large rainfall and snow volumes. However, runoff from most of the Sierra rivers is highly

regulated by dozens of dams and water diversions, which has significantly reduced the total runoff reaching the San Francisco Estuary and altered the seasonal patterns of that runoff and its sediment load (Krone 1979, Nichols *et al.* 1986).

The effect of these anthropogenically modified, climate driven runoff events on tide level and salinity is significant and highly unpredictable. Restoration outcome can be strongly influenced by the timing of restoration relative to drought and wet years (Malamud-Roam 2000, Baye *et al.* 2000) and through the combined actions of tidal water levels and salinity as they affect vegetation colonization and emergence patterns and aquatic organism life cycles. However, the unpredictable nature of these processes means that restoration planning efforts generally do not have the ability to incorporate their effects beyond selecting when to open a site to the tides.

2.2 Surface Exposure and Desiccation during Lower Tide Levels

An important and oft-overlooked phenomenon of San Francisco Estuary tides is the seasonal pattern of time of day at which the lower high tide occurs and thus duration of daytime exposure to the air. Exposure leads to desiccation through the combined actions of wind, sun, and heat and is a major influence on intertidal deposits globally (Eisma 1998). Currently, the lower high tide occurs during the daytime in the summer months and during the night-time in the winter months. Conversely, the higher high

tides occurs at night during the summer months and during the day in winter months. Malamud-Roam (2000) determined through examining several hundred years of predicted tides that this pattern changes on an approximately 300-year cycle.

Desiccation helps to consolidate the sediment surface, leading to two related phenomena that influence geomorphic process – lowering the ground surface elevation, which increases the inundation period, and increasing sediment strength, which increases resistance to erosion (Amos *et al.* 1988, Whitehouse and Mitchener 1998). Desiccation processes are stronger during summer months with higher sun angle, longer days, warmer air temperatures, and increased frequency and magnitude of afternoon winds (Conomos *et al.* 1985).

The single greatest characteristic of intertidal environments of every type around the globe is the decreasing tidal inundation frequency with increasing elevation. This inverse relationship exerts a fundamental control on many physical and biological conditions (e.g., Ricketts *et al.* 1968, Teal and Teal 1969, Nixon 1980, Josselyn 1983, Nichols and Pamatmat 1988, Mitsch and Gosselink 2000). In the case of an evolving tidal marsh restoration site, this inverse relationship translates to fewer of the lower high tides in a mixed, semi-diurnal tidal regime being high enough to overflow channel bankfull with a consequent decrease in marsh plain inundation frequently.

Combining this basic tidal characteristic with the San Francisco Estuary's seasonal pattern of daytime lower high tides in the warm and windy summer months and

elevation increases over time at evolving restoration sites creates environmental conditions conducive to desiccation of newly deposited sediments. These relationships suggest there may exist a threshold elevation at which desiccation and consolidation on the one hand and ongoing deposition on the other hand reach some level of balance in cumulative magnitude that either precludes or greatly limits ongoing net accretion until the time when vegetation becomes established. As vegetation colonizes a restoration site, these desiccation processes would presumably diminish in effect because the vegetation partially shields the surface from wind and sunlight.

2.3 Sediment Supply and Transport

Restoring intertidal marsh elevations through natural deposition requires a supply of suspended sediment transported into the restoration site, the deposition of that sediment load, and the long-term retention of that deposited sediment. In the San Francisco Estuary, there are three possible sources of suspended sediment to the water column: watersheds, the Pacific Ocean, and resuspension of estuarine sediments. Watershed inputs, primarily from the Central Valley, comprise 80-90% of total sediment inputs and have been the primary of past work evaluating sediment inputs into the San Francisco Estuary (Krone 1979 and 1996; Ogden Beeman & Associates and Krone 1992). Oceanic inputs therefore are not addressed here.

2.3.1 Watershed Inputs

Watershed sediment inputs into the San Francisco Estuary are the dominant source of new sediment into the system (Krone 1979, Atwater *et al.* 1979). The Central Valley of California drains 40% of the state and comprises 80-90% of the sediment entering the system. Most of this sediment loading occurs during the winter and spring months coincident with periods of maximum runoff, and consists largely of fine silts and clays (Krone 1979).

However, the magnitude of that supply has undergone significant changes through human intervention. Gilbert (1917) estimated that hydraulic gold mining in the Sierra Nevada, which took place from the middle of the 19th century until its cessation in 1884, deposited 1.1 billion cubic yards of sediment in the Estuary through 1914. Gilbert (1917) further stated that the hydraulic mining sediment continued to enter the Estuary at the time of his study, and Krone (1979) suggests that additional amounts of sediment were lost to the system. Jaffe *et al.* (1996) estimated that since the 1950s, this pulse of sediment has begun to erode from the northern embayment in the Estuary, San Pablo Bay.

Construction of dams throughout the Central Valley decreased sediment loads into the Bay. From 1909 until 1966, 86 percent of the Estuary's sediment came from the Central Valley. Since the 1960s, inputs have markedly decreased because sediments have been retained in reservoirs (Schoellhamer 1996). As a result, sediment loads into

the Bay in the early 1990s were approximately 50 to 70 percent of their pre-1960 levels.

2.3.2 Sediment Resuspension

Resuspension of estuarine deposits from shallow intertidal and subtidal flats through wind-wave action is the second major supply of suspended sediment to the water column. San Pablo Bay consists of broad expanses of shallow estuarine deposits (see Map 1-1 in Chapter 1). Much of this resuspended estuarine sediment is subsequently deposited again within the Estuary (Krone 1979 and 1996). Resuspension of sediment from the Bay bottom requires flow velocities high enough to overcome sediment resistance to erosion. Four mechanisms contribute to current strength in the Estuary: tides, winds, freshwater inflows, and salinity-induced density differences. Wind waves and the spring-neap tidal cycle are associated with high suspended sediment concentrations in the San Francisco Estuary (Ruhl *et al.* 2001).

Tidal Currents

The daily rise and fall of the tides represent an important physical force contributing to sediment resuspension. The magnitude of this forcing function varies on a daily basis with the inequality of tidal heights and associated tidal ranges, on a roughly two-week lunar basis (the spring-neap tidal cycle), and on a seasonal solar basis (summer and winter solstices and spring and fall equinoxes). The spring-neap tidal cycle is a well documented physical process affecting suspended sediment concentrations throughout

the Estuary (Schoellhamer 1996). Ruhl *et al.* (2001) reported for San Pablo Bay that the highest spring tide-associated suspended sediment concentrations in July 1995 were located in the northern and northwestern parts of San Pablo Bay, where waters are shallow (less than 2m). The study site is located in this region of San Pablo Bay. Effective bed shear stress generated from tidal and wind currents decreases rapidly with increasing water depth (Dronkers and van Leussen 1988, Mehta 1993, Sanford 1994, Schoellhamer 1995, Jing and Ridd 1996, Eisma 1998).

Winds

Additionally, winds generate a shear on the water surface that influences tidal flow. In periods of strong wind, these flows erode sediment from the Bay bottom, especially in shallow areas. Schoellhamer (1996) found that the greatest South Bay sediment concentrations occur during summer afternoons when the strongest winds typically occur. Ruhl *et al.* (2001) noted that early spring conditions of higher sustained winds in combination with less consolidated bed sediment deposited from the winter and spring runoff events yield conditions favorable for resuspension.

2.3.3 Sediment Transport

Once sediments are suspended in the water column, tidal currents are the primary forces causing sediment transport, though other currents especially wind-generated currents in shallow water play a lesser but important role (Schoellhamer 1996, Eisma 1998). Salinity-density currents originate with the onset of winter storms; freshwater

inflows push down through the Central Bay, lowering water density. The saltier, higher density water moves seaward along the Bay's bottom and is replaced by fresher, lower density water flowing near the surface. The same mechanism also occurs, but at a much smaller scale, from local freshwater stream discharges. Finally, prop wash from boats moves sediments as well. For all these currents, the greater its magnitude the larger and greater amount of suspended sediments is transported around the Bay.

Spring-Neap Tidal Cycles

During spring tides, shorter duration slack water periods limit sediment deposition and consolidation of newly deposited sediment. During neap tides, longer duration slack water periods promote sediment deposition and bed consolidation. Consequently, sediments accumulate in the water column as spring tides approach and slowly deposit as neap tides approach (Schoellhamer 1996). In the South Bay, these conditions result in sediment transport from shallow areas to the main channel during spring tides and the reverse during neap tides, with net transport toward the shallow margins (Schoellhamer 1996).

Seasonal Cycles

Sediment transport is also affected by season. During summer, diurnal breezes generate wind waves that increase sediment concentrations, resulting in a landward flux of suspended sediments in shallow water and a seaward flux in deeper channels. During winter, lighter winds, lower suspended solid concentration, and greater variance in wind direction result in less sediment transport.

Role of Bathymetry

Though sediment transport depends upon many factors including tidal currents, winds, freshwater runoff and longitudinal density differences, these forces interact with the Bay bathymetry (depth) to control sediment transport and distribution (Schoellhamer 1996). To understand the effects of the various forces transporting sediments, understanding the effects of the Bay's bathymetry provides context.

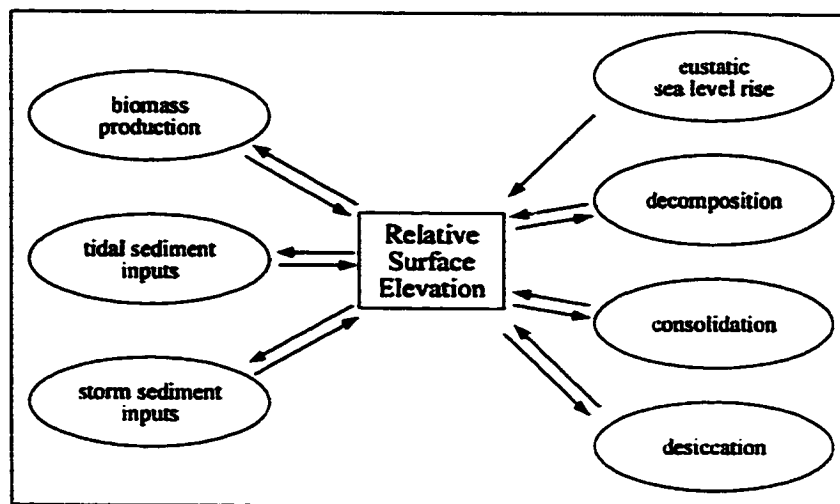
On submerged tidal flats, wave action predominates over current velocity as a distributing force (Sustar 1982). Variation in sediment grain size correlates directly with wave energy distribution. In other words, bigger waves move larger sediments. In deep-water areas, current velocity is the predominant estuarine force. Currents reach a maximum velocity at the channel's center and diminish towards the banks. Thus, bathymetry determines which tidal forces most affect sediment transport.

2.4 Tidal Marsh Restoration

Tidal marsh restoration on diked, former tidal marshlands (often called "impoundments") has been ongoing in the San Francisco Estuary since the 1960s and has been occurring with greater frequency elsewhere around the United States and in the United Kingdom (Goals Project 1999, Weinstein and Kreeger 2000, Callaway 2001, French and Reed 2001, Zedler 2001). In addition to these intentional restoration efforts, abandoned levee failures (e.g., caused by storms) have occurred in the past

going back at least to the 1930s in the San Francisco Estuary (e.g., Whale's Tail marsh in Hayward) and in the United Kingdom (French *et al.* 1999). Most marsh restoration efforts are undertaken for ecological or coastal erosion protection purposes (French and Reed 2001).

Figure 2-3. Controls on Relative Elevation



Processes on the left lead to increases in relative ground surface elevation, and processes on the right lead to elevation decreases. Feedback mechanisms exist with these processes and elevation and in some cases with each other.

Source: *adapted from Callaway (2001)*

2.5 Channel Formation Processes

Channel network morphology develops through the combined action of water flow and sediment transport that builds and shapes the channel-marsh plain system (Leopold *et al.* 1964, Knighton 1984, Allen and Pye 1992, French and Stoddart 1992). The mechanisms through which these two primary controls operate are in turn

influenced by extrinsic environmental variables (e.g., tidal range, wind, salinity) and intrinsic structural variables (e.g., elevations, antecedent land forms, bank vegetation, benthic and epibenthic organisms) (Pestrong 1965, Garafolo 1980, Green *et al.* 1986, Collins *et al.* 1987).

What we are interested in for restoration purposes are the processes by which the channel network develops and in particular what mechanisms play a central role in leading to network development. It must be pointed out that we do not know whether these processes are the same as those which took place in the evolution of Holocene tidal marshlands. Specifically, we do not yet know whether the specific path that restoration projects follow (i.e., rapid growth) leads to similar or different equilibrium channel morphology relative to natural marshes that evolved much more gradually as rates of sea level rise dropped during the Holocene.

2.5.1 Sediment Deposition

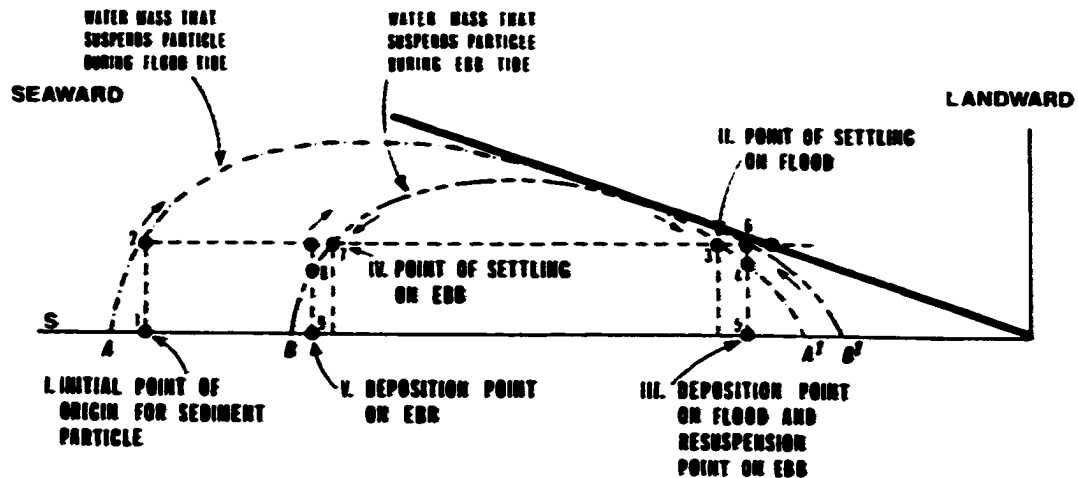
Sediment deposition occurs when tidal shear velocities drop below the settling velocity of the material in suspension, which is a function of grain size and grain density (Dingman 1984, Knighton 1984, Mehta 1994 and 1989). Under these conditions, the shear stress of the flow is inadequate to maintain material in suspension. Estuarine suspended sediments often comprise a large fraction of fine silts and clays which, when exposed to brackish and saline estuarine water, coagulate into

flocs that are of larger grain size but often of much lower density due to the loose structure of the floc (Mehta 1993, Li *et al.* 1993). Consequently, settling velocities are very low and the relationships between grain characteristics and settling velocity are very complicated and can depend not only on absolute flow velocities but also on those factors that control the flocculation process (e.g., salinity, concentration of suspended sediment, flow turbulence) (Mehta 1989, French and Clifford 1992). Sufficiently low velocities arise only in a few circumstances: at slack tide, where tidal flows of different source directions meet (such as near the central levee; see Figure 7), and where flow resistance is large due to form drag from highly sinuous channels and reduced cross sectional area as channel size reduces headward and due to vegetation (Allen and Pye 1992, Leopold *et al.* 1993).

The nature of the sediment in suspension also affects its potential for deposition in terms of grain size and flocculation (Mehta 1993, Frey and Basan 1978). Elevation affects the potential for deposition in two ways: through the frequency and duration of inundation of the ground surface by tidal waters (a measure of the window of opportunity for deposition) and through the timing of velocity maxima associated with the forcing tidal wave and how that tidal wave interacts with the ground surface (a measure of magnitude of the controlling forces when the depositional “window” is open) (Green *et al.* 1986, French and Stoddart 1992). Finally, fine-grained sediment has a net landward transport through a process termed the settling-scour lag effect driven in part by tidal asymmetry, the difference between critical deposition and erosion shear stresses, and the effects of consolidation, changes in pore water salinity,

and desiccation (Frey and Basan 1978, Eisma 1998). Figure 2-4 illustrates this process.

Figure 2-4. Settling – Scour Lag Effect on Net Estuarine Sediment Transport



This figure shows the hypothetical effect of settling lag (flood tide) and scour lag (ebb tide) on a sediment particle. S = substrate surface. Roman and Arabic numerals indicate presumed hydraulic and sedimentologic events, and letters indicate particle trajectory. During repeated cycles, the net movement of an ideal grain should be successively more landward.

Source: Frey and Basan (1978)

One process whereby channel network development can occur is through differential accretion. In this manner, flow concentrates in slight topographic depressions and incipient channels can begin to form. As deposition continues, accretion outside these incipient channels occurs. The incipient channels, however, experience either slower deposition but still accrete, cease deposition and maintain their invert elevation, or degrade through erosion. The consequence is that the channel banks build vertically as the marsh plain accretes and a channel is thereby created (Pestrong 1965). As the overall elevation of the system continues to rise, these incipient channels continue to

form headward and along tributary paths, thereby extending the network (Knighton *et al.* 1992). Further, flow velocities generally are not high enough to cause bank erosion and lateral migration, thus the planimetric form of the channels tends to be preserved as the system accretes (Collins *et al.* 1987). This component of the differential accretion process, known as adoption of antecedent planform morphology, suggests the importance of the initial conditions in determining equilibrium channel morphology. Gabet (1998) found in tidal marshes in China Camp State Park about 12km from the study site that, while bank slumping occurs and appears to indicate relatively high rates of bank erosion, longer-term estimated lateral migration rates were far smaller than the bank erosion would suggest, due in large part to the slump blocks armoring the bank from further erosion until the slumps erode away.

2.5.2 Sediment Entrainment

The second process of channel network development is erosion, both of underlying site soils and of tidally deposited sediment (Pestrong 1965, Frey and Basan 1978, Bayliss-Smith *et al.* 1979, Collins *et al.* 1987, Knighton *et al.* 1992). Erosion can be at the grain scale such as mobilization of a fluid bed or at the form scale such as failure of an overhanging bank. In all instances, erosion requires the shear stress associated with the flows to exceed a critical value. In river systems, this critical shear stress is essentially the same value for erosion and for deposition (though some difference does exist due to grain packing and bed armoring) (Knighton 1984, Dingman 1984). In tidal

systems, however, this difference is much greater because cohesion adds strength (resistance to erosion) in two ways. At the grain scale cohesive sediments undergo elastic deformation before they can be entrained due to the electrical bonds of the clay and silt particles interacting where salinity conditions prevail (Mehta 1989 and 1993). At the form scale cohesive sediments offer considerable structural integrity and erosion tends to occur as large block failure along channel banks (Pestrong 1965, 1972a, and 1972b; Knighton 1984; Collins *et al.* 1987; Gabet 1998). Channel bank vegetation vastly increases strength and thus resistance to erosion (Pestrong 1965, 1972a, and 1972b; Garafolo 1980; Collins *et al.* 1987). One common mechanism to generate excess shear stress where the time-averaged flow velocities would not appear to create such conditions is turbulence. Turbulent bursts increase velocities and shear stresses at small spatial and temporal scales and create upward velocities that exert lift force (French and Clifford 1992, French *et al.* 1993).

Chapter 3.0 Site Description and Restoration Design

This research began with identification of site attributes necessary to answer the questions described in Chapter 1. Section 3.1 describes these attributes. Section 3.2 describes the history and suitability of the selected site, the Petaluma River Marsh. Sections 3.3 and 3.4 put this site into a landscape context, describing the surrounding land uses and nearby wetland restoration projects, respectively. Section 3.5 describes the restoration project constructed at the research site.

3.1 Attributes of a Suitable Study Site

There are five site attributes that contribute to the suitability of a study site for answering the research questions posed in Chapter 1: subsided, recently restored, simply hydrology, rapidly changing, and of reasonable size. Each of these attributes is described in the following sections.

3.1.1 Typical Subsided Bayland

The most significant attribute of restorable diked baylands is their subsidence below marsh plain elevation. The magnitude of subsidence typically ranges between 0.3-3 m (1-10 ft) in the Estuary (Goals Report 1999), and 3-8 m (10-25 ft) in the Sacramento-

San Joaquin river delta that drains into the Estuary (DWR 1993). This characteristic poses a large challenge for effective, sustainable and successful marsh restoration because the geomorphic components of a tidal marsh must be recreated through human intervention promoting natural processes. To provide research results applicable to a broad range of restoration efforts, the research site must be a subsided site. Since this research focuses on the San Francisco Estuary rather than the Sacramento-San Joaquin river delta, subsidence in the 2 to 3 m range is ideal.

3.1.2 Recently Restored

A primary site criterion is that of recent restoration so that, during the research period, the site would be in the midst of evolution from pre-existing conditions to an ecologically functioning tidal marsh. This early post-construction period generally coincides with the project monitoring (often 5-year efforts). During that time, sites typically receive greater attention and it provides the opportunity to take corrective measures if necessary. Consequently, having detailed data for such an evolutionary process can yield indicators that describe the change occurring with comparatively simple field methods.

3.1.3 Undergoing Rapid Change

An ideal site attribute is rapid change in geomorphology such that strong differences can be discerned in short time periods. Many of the reasons explained immediately above about recently restored sites apply equally to the benefits of undergoing rapid accretion and site evolution.

3.1.4 Simple Hydrology to Minimize Variables

A desirable site criterion is to have as simple of site hydrology as possible. Simple hydrology minimizes or eliminates as much uncontrolled variability as possible. Site hydrology is affected by tidal exchange, rainfall, runoff, flow constrictions, and site topography. Thus, a site with as few of these influences as possible increases the ability to draw more robust conclusions.

3.1.5 Reasonable Size

The final criterion used to select a research site is that of “reasonable” size. Many geomorphic processes operate across a broad range of spatial scales (e.g., Leopold *et al.* 1964). Recent research considering scale effects in geomorphic processes of tidal wetlands has suggested some scale dependency (Rinaldo *et al.* 1999). What defines a

“reasonable” size is difficult to evaluate. Further complicating consideration of size is that the pool of potential research sites is not large and thus one does not have much control over this attribute.

Planned restoration projects in the region are considering sites up to several thousand acres in size. Thus, a research site of a few acres would likely be too small to provide much meaningful results for such large-scale projects.

3.2 Petaluma River Marsh Restoration Project Site

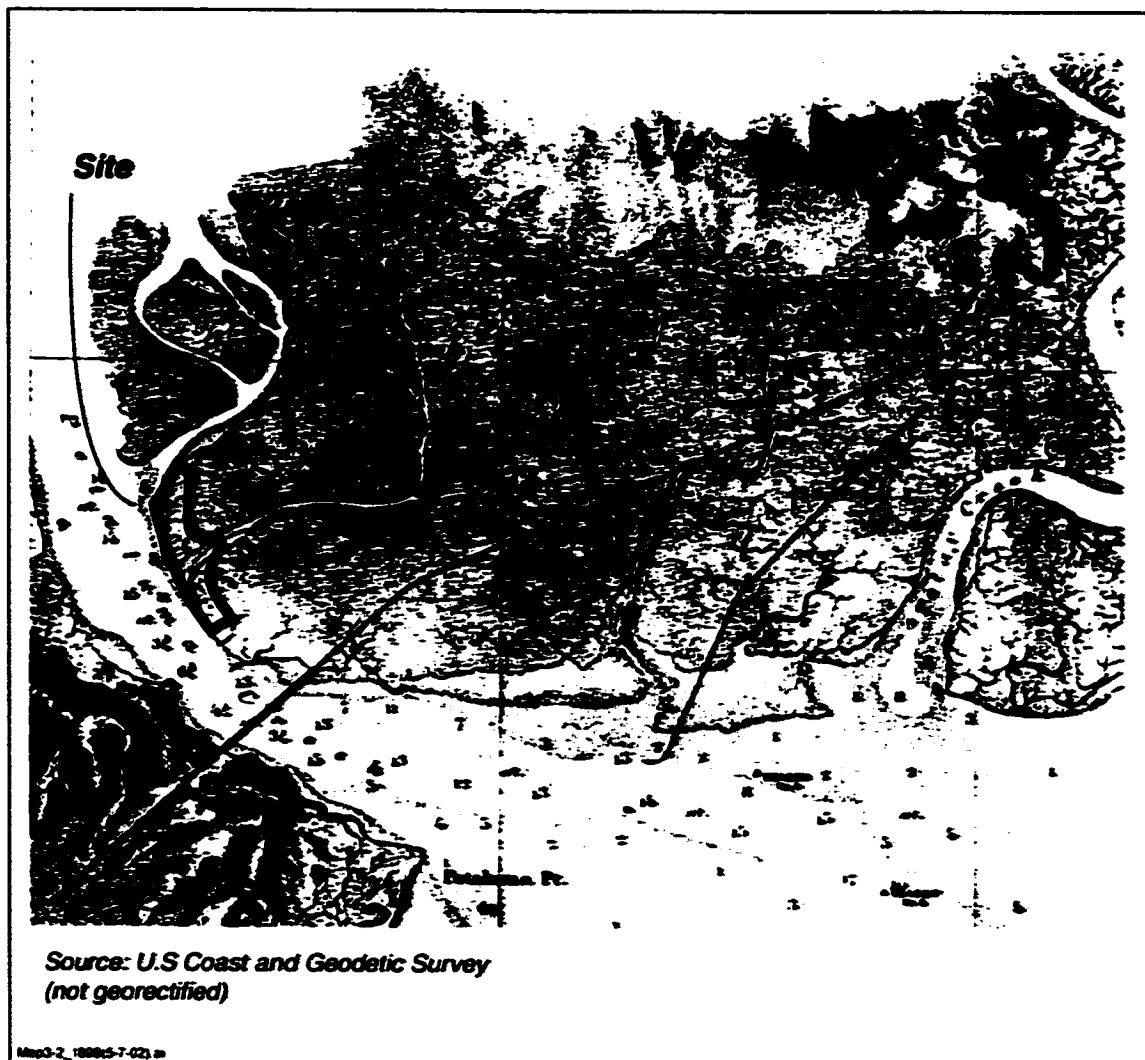
I selected the 19-hectare (48-acre) Petaluma River Marsh Restoration Project, commonly known as “Carl’s Marsh,” for this research (Map 1-2 in Chapter 1). This site is located in southern Sonoma County just upstream of the Petaluma River confluence with San Pablo Bay (see Map 1-1 in Chapter 1). The California Department of Fish and Game (CDFG) in cooperation with the Sonoma Land Trust (SLT) restored this agricultural diked bayland to tidal action in August 1994.

3.2.1 Site History

The Petaluma Marsh Restoration project site had been estuarine tidal salt marsh prior to being diked. Map 3-1 shows the portion of the 1898 update of the 1863 U.S. Coast and Geodetic Map for the site vicinity, with most of the map in the study site vicinity

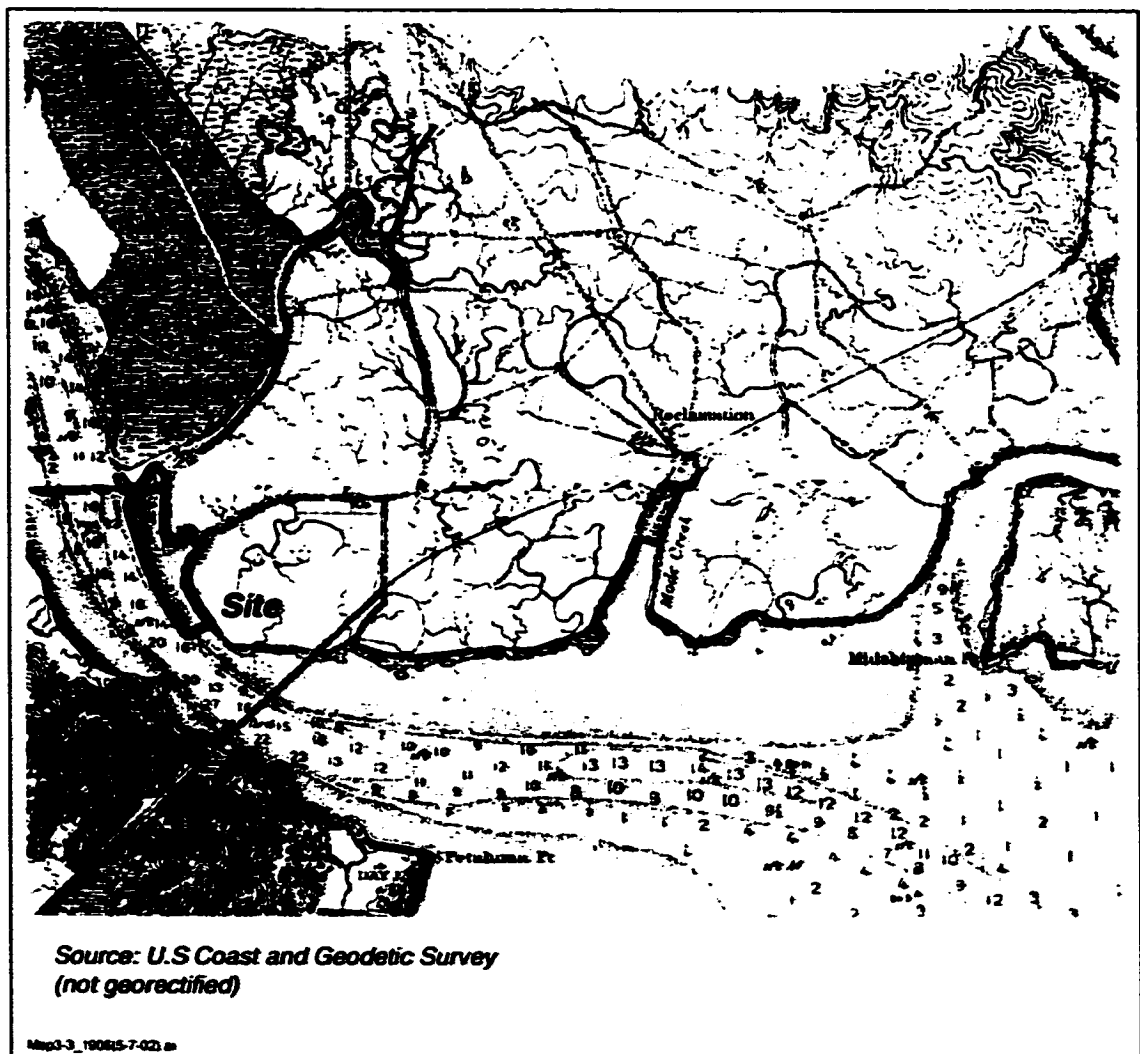
being from 1863. During this 1863 to 1898 period, most of the San Pablo Bay tidal marshes remained intact and considerable quantities of hydraulic mining debris from the Sierra Nevada had begun to deposit in San Pablo Bay (Jaffe *et al.* 2000, Gilbert 1917).

Map 3-1. Site Vicinity Map, 1898 Update of 1863 USCGS Map



Map 3-2 shows the same area in 1906. In this short 8-year interval, much of the tidal marsh fringing San Pablo had been diked and converted to agricultural use. The only tidal marsh remaining at that time was upstream along the Petaluma River north of the study site, along the northern banks of Novato Creek to the southwest of the study site, and the study site itself (Map 3-2).

Map 3-2. Site Vicinity Map, 1906 USCGS Map



Only two segments of tidal marsh in the entire San Pablo Bay region were never diked. The 900-ha (2,200-ac) Petaluma Marsh is about 5 km (3 mi) upstream of the study site. Another 300 ha (750 ac) is at the mouth of Gallinas Creek in Marin County about 10 km (6 mi) south of the study site; about a third of this marsh is within what is now China Camp State Park (Map 1-1 in Chapter 1).

Since being diked from the bay in the late 1950s or early 1960s (Jones 1992), the site had been in agricultural production as an oat-hay field. Oat-hay crops require annual disking, planting, and harvesting. These agricultural activities largely eliminate the geomorphic attributes of the original tidal marsh, such as the channel network. Crop irrigation is entirely from rainfall and runoff and subsequent shallow groundwater management via pumps. Subsidence varies in part based on soil types in the original tidal marsh. Marsh plain soils contained higher organic matter content from accumulated plant matter and channels were typically more mineral in nature. The greater oxidation-driven soil decomposition of the organic marsh plain soils (Brady and Weil 1996, Mitsch and Gosselink 2000, Atwater *et al.* 1979).

At the time of restoration, this site had subsided well below local mean higher high water (MHHW) marsh plain elevations. Reconstructing baseline topography relies on several data sources:

- **Sediment pins installed by CDFG during project construction yield baseline topography between -0.4 to 0.1m NAVD (Appendix A).**

- **One CDFG hand-drawn baseline map with about 30 points yield baseline topography in the range of 0.5 to 0.8m NAVD (data provided by Carl Wilcox, CDFG, personal communication, 1996). Data collection methods were not available to evaluate uncertainty.**
- **Five sediment cores collected in March 1997 by the University of California at Berkeley Department of Geography Field Course that yielded deposited sediment thickness between 0.48 and 1.6m but no ground surface elevation data for any of the coring locations.**
- **An undergraduate student paper from the 1992 University of California at Berkeley Environmental Sciences program examining wetland delineation issues that noted shallow topographic swales on the farm field but otherwise provided no elevation data (Jones 1992).**

These data describe a site with some amount of topographic variability with the most reliable data appearing to be the sediment pins since they have good baseline and follow-up elevations, are spread out around the site, and are not likely to have shifted considerably. Based on these data, I estimate baseline topography to be around 0m NAVD, or approximately 1.9 m (6.2 ft) below local MHHW marsh plain elevations.

3.2.2 Site Suitability

The Petaluma River Marsh provided nearly all the desired attributes described in Section 3.1. Each of these attributes is described briefly below.

Typical Subsided Bayland. This site had subsided to local mean lower low water (MLLW) elevations, or approximately 1.9 m (6.2 ft) below local mean higher high water (MHHW). MHHW is the typical elevation for pickleweed-dominated tidal salt marsh in the San Francisco Estuary (Goals Project 1999) and the target equilibrium elevation for the site (USACE 1993).

Recently Restored. CDFG and SLT restored this site to tidal action on 24 August 1994. Field work began in early 1997, approximately 2.5 years after restoration.

Simple Hydrology. Study site hydrology exhibits a number of key simplifications that make for an ideal research site:

1. **The site has direct tidal exchange with its source.** The Petaluma River directly feeds the site (Map 3-3) and there are no flow constrictions.
2. **The tidal source is predominantly estuarine.** The Petaluma River is effectively an extension of San Pablo Bay as a very large (225-m/750 ft wide) slough with tidal influence extending several kilometers upstream

(Map 3-3). Watershed discharge is predominantly storm-driven; a small year-round wastewater treatment plant discharges upstream but those flows are a very small fraction of the tidal prism (Hurley, pers. comm., 1998).

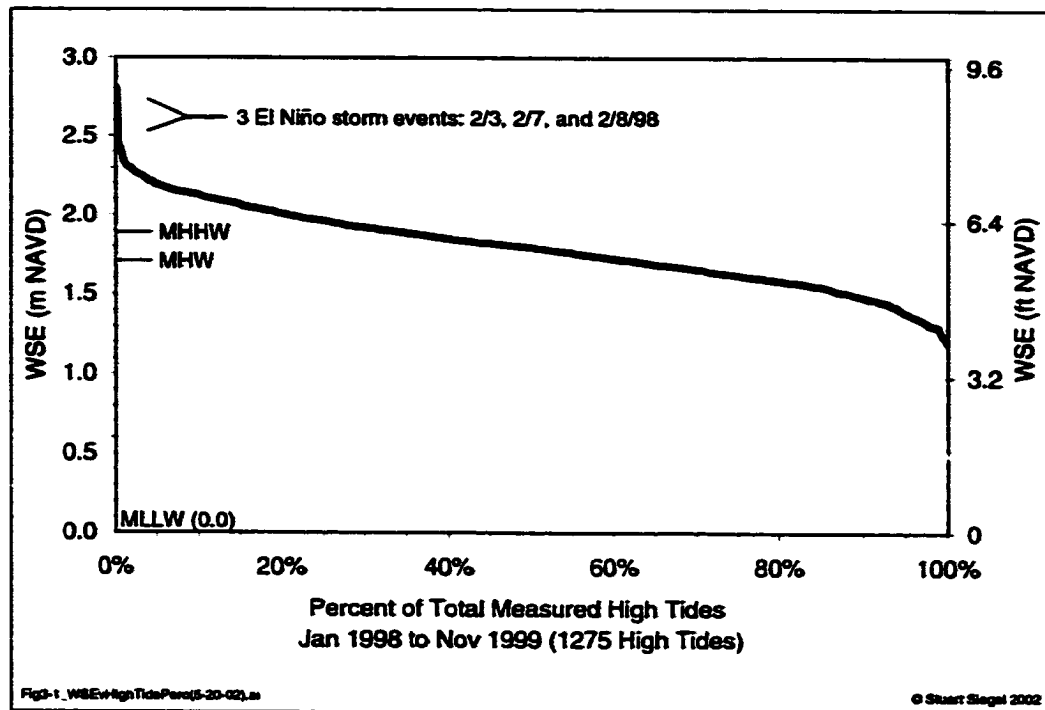
3. The site is essentially an enclosed basin with no additional watershed.

The predominant water supply to the site is tidal exchange through two levee breaches, one at each end of the basin (Map 1-2 in Chapter 1). Direct rainfall contributes an annual volume roughly equivalent to two spring tides (there are about 175 spring tides per year). Steep levee banks (5:1 or steeper) eliminate any additional watershed area. The lowered outboard (western) levee that separates the site from the Petaluma River (Map 1-2) has an average elevation of 0.25 m (0.75 ft) above local MHHW. Of the 1275 high tides recorded at the site during the 1998-1999 field effort, only 153 (12%) reached or exceeded the levee elevation. Only 40 of those tides (3%) exceeded average levee elevation by more than 0.15 m (0.5 ft). See Figure 3-1. This monitoring period coincided with the 1998 El Niño event, which raised water levels throughout the estuary and thus inflated this percent inundation data. The outboard levee is heavily vegetated and consequently very little tidal exchange occurs except during the highest of these extreme high tide events.

4. Local sediment supply is very high owing to the close proximity of vast intertidal mudflats in San Pablo Bay (Map 3-3) and to the estuarine

sediment dynamics of large channel entrances (e.g., the Petaluma River) into shallow, open embayments (e.g., San Pablo Bay) (Ruhl *et al.* 2001).

Figure 3-1. Water Surface Elevations versus High Tide Percent Inundation, Jan 1998 to Nov 1999



This data plot shows the water surface elevations of 1275 high tide events measured at the study site between January 1998 and November 1999 as the percent of high tides that exceeded a given elevation. These data are influenced by the large 1997-1998 El Niño events that raised overall coastal and estuarine water levels and led to several major storm events that produced rare high-water events.

Undergoing Rapid Change. The mouth of the Petaluma River is well known for its high sedimentation rates. Port Sonoma Marina, a small boat harbor located a few hundred meters south of the site, requires frequent dredging to maintain navigable depths. The U.S. Army Corps of Engineers public notice for the Petaluma River Marsh Restoration Project (USACE 1993), recognizing these conditions, reported

estimated sedimentation rates at the site of approximately 0.5 m/yr (1.5 ft/yr) initially based on monitoring data for two nearby tidal basins, the Port Sonoma Marina immediately to the south and the Bahia residential development lagoon across the river to the west (Map 3-3). Beginning the research 2½ years after restoration would suggest at least 1.2 m (4 ft) of sediment would have accumulated out of a total deficit of 1.9 m (6.2 ft).

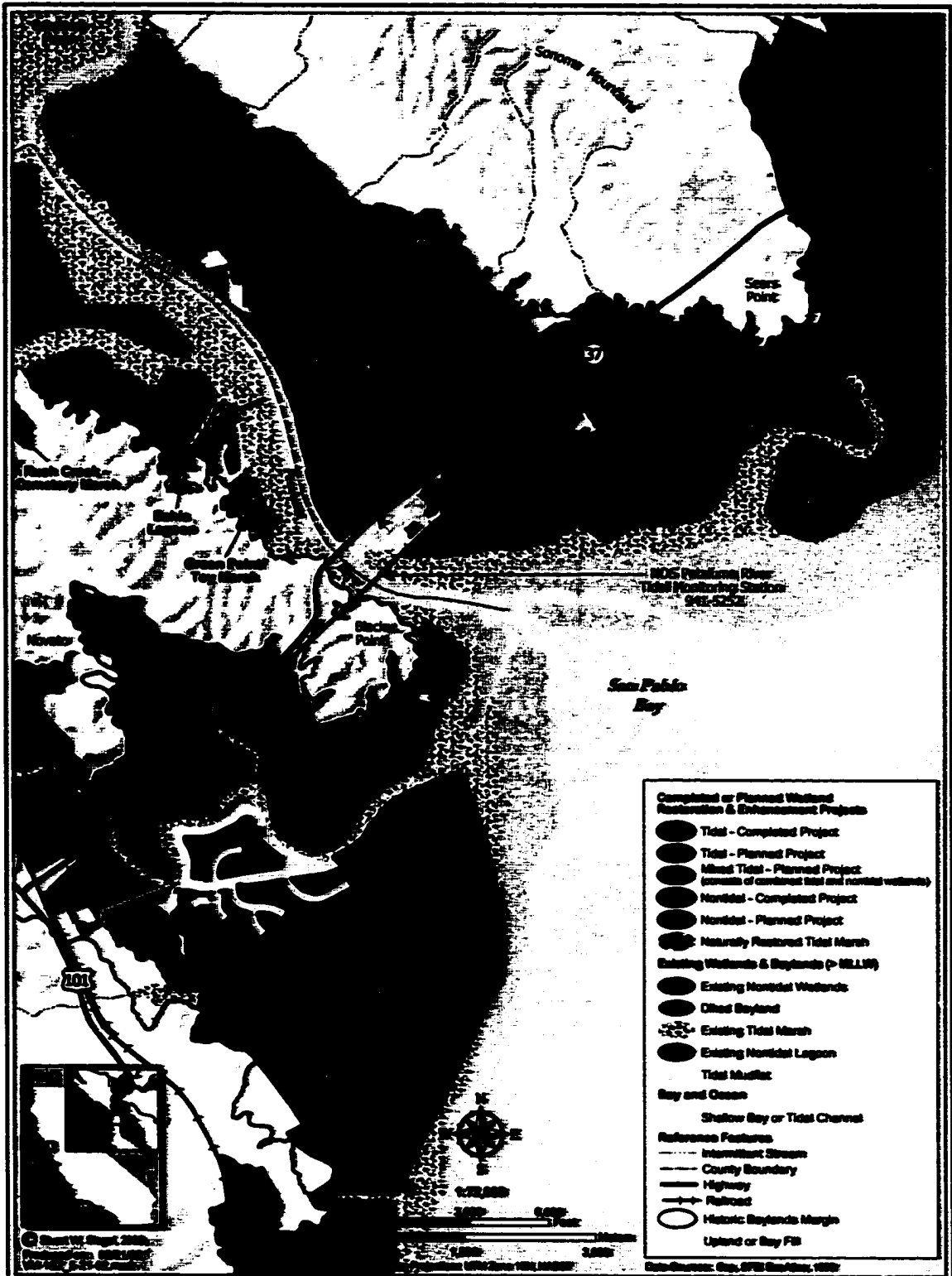
Reasonable Size. The final target attribute is for site area to be “reasonable” in size. Given that planned restoration projects are now reaching sizes of several thousand hectare, the importance of scale effects cannot be underestimated. Recent research on scale factors in estuarine tidal wetland channels (e.g., Fagherazzi *et al.* 1999) suggests that relationships between tidal channel network spatial extent and channel geometry (especially width) diverge from log-linear patterns with increasing channel width. The Petaluma River Marsh site, at 19 ha (48 ac), was not the largest of the candidate sites. It is fairly large in the sense of exhibiting a large tidal prism at the outset (360,000 m³ or 300 acre-feet) that can carry out geomorphic work at levels meaningful to larger-scale restoration projects. Caution is warranted when making such extrapolations in relation to how the results would be used.

Napa Salt Pond 2A, at 210 ha (520 ac) and restored in 1995, was the second-best fit overall. The primary reason I opted not to use Pond 2A was that its land use history as a salt evaporator pond had limited its subsidence to only half that of the Petaluma River Marsh. Restoration outcome as a function of baseline subsidence underlies this

research, and that of the CalFed-funded BREACH II project (Simestad *et al.* 1999), because of its prevalence at suitable restoration sites throughout the San Francisco Estuary. Diked, subsided baylands in agricultural use make up a large proportion of the suitable restoration sites in the North Bay (see Map 1-1 in Chapter 1). Salt ponds generally have not undergone much more than 1 m (3 ft) of subsidence because salt operations predominantly maintain them as open water. The only appreciable salt pond subsidence in the Estuary is between Mountain View and San Jose and this subsidence is due to groundwater withdrawal (Siegel and Bachand 2002). Comparing outcomes between Pond 2A and the Petaluma River Marsh would likely yield further insight into processes considered here and elsewhere.

3.3 Surrounding Land Uses

There are a number of landscape features surrounding the study site that influence site evolution and/or provide insight regarding possible future conditions at the site. Map 1-2 in Chapter 1 shows the immediate surroundings, Map 3-3 shows the general vicinity, and Map 1-1 shows the entire San Pablo region which places the site into a larger geographic context.



Vicinity Map
 Petaluma River Marsh, Sonoma County, California

Map
 3-3

3.3.1 Petaluma River

The study site adjoins the Petaluma River approximately 1 km (0.6 mi) upstream of its confluence with San Pablo Bay (Map 3-3). At this location, the Petaluma River is essentially a large tidal slough roughly 225 m (750 ft) wide. Aside from a relatively small year-round wastewater treatment plant discharge upstream (Hurley, 1998, pers. comm.), Petaluma River fluvial discharge is highly seasonal. The United States Geological Survey maintained a gauging station upstream of the study site from 1949 to 1963 (USGS 2000). During this period, peak storm discharges ranged from a drought low of 70 cubic feet per second (cfs) or 2 cubic meters per second (cms) to the late 1955 flood discharges of nearly 1,500 cfs (about 40 cms). Median annual peak discharge was 775 cfs (22 cms) during this period.

The Petaluma River is a federally maintained navigation channel. The U.S. Army Corps of Engineers maintains a navigation depth of -8.0 ft (-2.1 m) MLLW from the open waters of San Pablo Bay past the study site and upstream to the City of Petaluma. Dredging records date back to 1937. The lower reaches of the Petaluma River near the study site have shown minimal sedimentation or erosion, and the channel across San Pablo Bay mudflats that links the river to the San Pablo Bay deepwater navigation channel is dredged approximately every eight years (LTMS 1996).

3.3.2 San Pablo Bay

The northwest corner of San Pablo Bay is located approximately 1 km (0.6 mi) southeast of the study site (Map 3-3). San Pablo Bay is fringed with intertidal mudflats along its western and northern boundaries, and much of it is shallow subtidal less than 5.5 m (18 ft) below MLLW. These broad intertidal and subtidal flats provide a sediment supply that readily erodes by wind and storm waves across San Pablo Bay, that tidal- and wind-driven currents circulate around San Pablo Bay and up the Petaluma River, and together provide a relatively large suspended sediment supply in the water column a majority of the time (Krone 1979). These flats are likely the predominant sediment source for the study site, at least through most of the year, since fluvial discharge from the Petaluma River watershed (gauged by USGS from 1948 to 1963) is largely seasonal in nature. Summer northwesterly sea breezes comprise a majority of the wind energy exerted on San Pablo Bay, pushing shallow water across the mudflats (Dingler, pers. comm., 2000).

3.3.3 Black Point and Bahia Residential

Two residential areas are located on the western side of the Petaluma River in the vicinity of the study site. The Bahia community is directly across the river from the study site and north of Highway 37, and the Black Point community is south of Highway 37 (Map 3-3). The Bahia community includes a tidal lagoon originally

constructed for small boat use but that instead has accumulated sediment rapidly and insufficient funds have been available for regular dredging. Consequently, sedimentation and marsh establishment provide additional comparison information to the study site (and served as one basis for predicted sedimentation rates referenced in the Corps public notice [USACE 1993]).

3.3.4 Diked Baylands in Agricultural Production

To the east and north of the study site are diked, subsided baylands in agricultural use for dry oat-hay farming and/or livestock grazing (Maps 1-1 and 3-3). These diked baylands extend north along the Petaluma River for about 5 km (3 mi) and east to the alluvial fans that drain the nearby Sonoma Mountains (Map 3-3). This “soft” upland edge is very rare throughout the San Francisco Estuary, as nearly every similar historic wetland/upland boundary has been developed. Consequently, tidal marsh restoration of these lands would provide an unique opportunity to create extensive wetland/upland ecotone, a rare habitat with considerable conservation importance (Baye 2000). How those restoration efforts may proceed could be influenced in part by the outcome at the study site.

3.4 Restoration Projects in the Surrounding Area

The study site is located within a region of the San Francisco Estuary that is currently undergoing numerous wetland restoration planning efforts (Map 1-1). Surrounding San Pablo Bay are more than 30 planned wetland restoration projects totaling over 7,000 ha (17,000 ac). Over 1,600 ha (4,000 ac) has already been restored. In addition to these constructed and planned projects, there remains another nearly 10,000 ha (24,000 ac) of diked baylands that could be restored (WWR 2002).

These restored and planned projects are largely on diked, subsided baylands in use for agriculture (14,000 ha or 34,000 ac). A portion of these lands, approximately 3,000 ha (7,300 ac), are on former salt evaporator ponds along the Napa River (Map 1-1). Most of the agricultural lands are subsided to similar elevations as that found at the study site. There have been only four constructed tidal marsh restoration projects in the North Bay larger than 40 ha (100 ac): Muzzi Marsh in Marin County (56 ha/138 ac) constructed with dredged material in 1976, Sonoma Baylands in Sonoma County (123 ha/303 ac) constructed with dredged material in 1996, Tolay Creek in Sonoma County (124 ha/306 ac) constructed in 1999 and relying on natural deposition, and Napa Salt Pond 2A in Napa and Solano Counties (211 ha/521 ac) constructed in 1995 and relying on natural deposition. All but Pond 2A have been subject to intense critique of their effectiveness, Muzzi for being too high, Sonoma Baylands for having a restricted tidal exchange, and Tolay for lower than expected surrounding elevations.

The Petaluma River Marsh is often cited as one of the most successful tidal marsh restoration projects in the San Francisco Estuary (e.g., Goals Project 1999, SSWWR 1998). Thus, lessons learned from this successful project, as identified through the research results from this study, will aid broader tidal marsh restoration efforts planned for the North Bay and elsewhere in the San Francisco Estuary. Pond 2A also falls into this category, and future efforts to compare these projects would be useful.

3.5 Petaluma River Marsh Restoration Design

The California Department of Fish and Game (CDFG) designed this project in coordination with the Sonoma Land Trust (SLT). The site's common name, Carl's Marsh, comes from Carl Wilcox at CDFG, who was instrumental in making this project happen and oversaw its design. The restoration design consisted of five discrete components, each of which is described along with their objectives. Map 1-2 in Chapter 1 illustrates these features.

Raise Inboard Levee

The inboard levee became the primary flood control levee for large amounts of land to the east and north of the site including State Highway 37 (Map 3-3). Consequently, the design included raising this levee to flood control heights (+9 ft NGVD or +12 ft NAVD or +3.7 m NAVD) using approximately 15,350 yd³ (11,700 m³) of soil

excavated from the site interior. All borrow areas were graded to eliminate depressions that may not drain effectively at low tide (USACE 1993).

Lower Outboard Levee

The design included lowering the existing western or outboard levee, converting it from flood control to high marsh elevations and to eliminate den sites for the invasive predator, red fox (letter from SLT to USACE May 18, 1994).

Construct Central Levee to PG&E Tower

The design included constructing an access levee to reach the Pacific Gas and Electric high-voltage electrical transmission line tower located in the center of the site (Map 1-2). Approximately 5,700 yd³ (4,400 m³) of soil was excavated from the site interior for this purpose (USACE 1993). Construction of this levee effectively divided the site into two basins, one northern and one southern of the levee, leaving a gap of about 40m at the end of a 125-m flow barrier.

Excavate Pilot Channels

The design included constructing pilot channels, 0.3 m deep and 3 m wide (1 ft by 10 ft) in both basins and connecting these channels to the levee breach locations. The purpose of these small channels was to promote future channel establishment and to ensure effective drainage of the site at low tide.

Breach Outboard Levee in Two Locations

The final step in construction included breaching the outboard levee in two locations, at the southwest and northwest corner of the project site. The design relied on

subjective estimates of necessary cross sectional area and assumed erosion would enlarge breaches as necessary (USACE 1993).

The expected outcome of these actions was rapid sediment accumulation initially, establishment of tidal marsh vegetation over time, conversion of the outboard levee to high marsh habitats, and establishment of a natural tidal marsh within 20-30 years including a marsh plain and tidal channel network typical to tidal marshes in the site vicinity (USACE 1993).

Small Parallel Berms

In addition to these design elements, project construction added a sixth key element, small parallel berms within the site. These berms were created from the “clearing and grubbing” process that preceded excavation of on-site soils for use in raising the inboard levee and constructing the PG&E access levee. Clearing and grubbing consists of removing surface vegetation and shallow surface soils that do not meet requirements for construction material. The contractor scraped this surficial material into linear berms, reported to be about 0.7 to 1m (2-3ft) tall and about 2m (6ft) wide at the base (Carl Wilcox, pers. comm. 1996). Berms were limited in extent to where borrow soils were obtained and thus did not cover the entire site. Berm spacing varied. Map 1-2 in Chapter 1 shows the berm locations.

Chapter 4.0 Methods

The purpose of this chapter is to describe the field and analytical methods employed to carry out this research. This chapter is organized into four sections:

- Continuous recording field instruments (Section 4.1)
- Periodic field measurements (Section 4.2)
- Remote sensing and Geographic Information Systems (Section 4.3)
- Calculating net sediment flux (Section 4.4)

4.1 Continuous Recording Field Instrumentation

The field instrument deployment took place at several locations at the site depending on the period and parameters being measured. The two main sampling stations were the South Channel-South Mudflat area and the North Channel-North Mudflat area (see Map 4-1). Instruments were mounted on deployment structures constructed in the field for this purpose (see Photo 4-1). Table 4-1 shows the deployment periods for each sensor type at each location. Not all instrument data collected is used here.

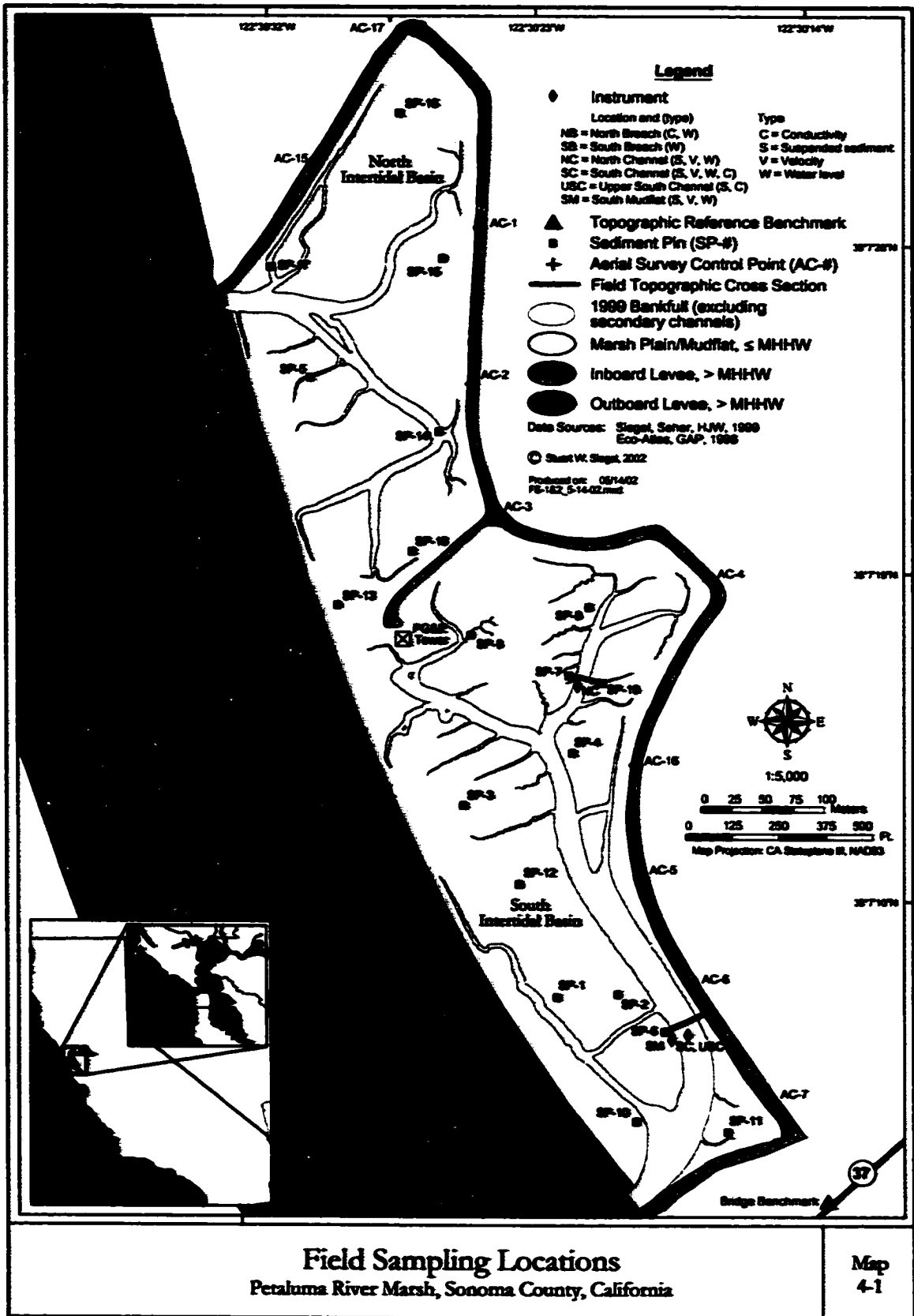


Table 4-1. Field Sampling Schedule

Location	Parameter	Equipment	Date																									
			1997				1998				1999																	
			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec		
Category 1: Continuously Recording Autonomous Field Equipment Data Collection																												
North Levee Branch (NB)	Water level	Troll 4000																										
		Troll 4000																										
		Troll 4000																										
		Troll 6000																										
		Troll 4000																										
Conductivity		Troll 8000																										
North Channel (NC)	Water level	Troll 4000																										
		Troll 4000																										
		OBIS-3																										
Suspended sediment	Current	ADV-F5																										
South Levee Branch (SB)	Water level	Troll 4000																										
Ratford Bridge (RB)	Water level	Troll 4000																										
South Channel (SC)	Water level	Troll 4000																										
		Troll 4000																										
		Troll 8000																										
Conductivity	Suspended sediment	Troll 8000																										
		OBIS-3																										
Current		OBIS-2																										
		ADV-F5																										
Upper South Channel (USC)	Water level	Troll 4000																										
		Troll 4000																										
		Troll 8000																										
Conductivity	Suspended sediment	Troll 8000																										
		OBIS-3																										
Current		OBIS-2																										
		ADV-F5																										
Upper South Channel (USC)	Water level	Troll 4000																										
		Troll 4000																										
		Troll 8000																										
Conductivity	Suspended sediment	Troll 8000																										
		OBIS-3																										
Current		OBIS-2																										
		ADV-F5																										

Table 4-1. Field Sampling Schedule, continued

Location	Parameter	Equipment	Date																								
			1997			1998			1999																		
			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Category 2: Periodic Field Measurements and Aerial Photography																											
Miscellaneous Activities																											
	Air photography																										
	Sediment pin reading - GDFG line 6																										
	Sediment pin reading - additional 14																										
Topographic Surveys																											
	Outer levee benchmark survey																										
	Inner levee benchmark survey																										
	Sediment pin topographic survey																										
	Sediment line topographic survey																										
	Sand lens topographic survey																										
	Inner levee cross section survey																										
	Outer levee cross section survey																										
	North breach cross section survey																										
	South breach cross section survey																										
	North channel cross section survey																										
	South channel cross section survey																										
	North breach staff gauging well																										
	North channel staff gauge																										
NC-NM structure benchmarks																											
SC-SM structure benchmarks																											

- Notes:
1. Numbers in each row represent day of month continuous recording started/ended (Category 1 activities) or occurred (Category 2 activities)
 2. Equipment deployment periods indicated by shaded boxes
 3. Trail 4000 (water level) and Trail 8000 (water level and conductivity) manufactured by In-Situ, Inc
 4. OBS-3 (suspended sediment) manufactured by Downing and Associates
 5. ADV-F5 (velocity) manufactured by Sontek, Inc
 6. Field topographic surveys performed with TopCon GTS-3 or 4 laser total station.
 7. Sediment pins consist of 1-inch PVC pipe (GDFG pins) or 2-inch PVC (additional pins)

Photo 4-1. Field Instrument Deployment Structure at South Channel-South Mudflat Stations



4.1.1 Water Level

I measured water level at five locations: South Breach (SB) (only briefly due to vandalism); South Channel (SC); South Mudflat (SM); North Channel (NC); North Breach (NB); and the nearby Railroad Bridge (RR) for determining tidal datums (see sampling locations in Map 4-1). These measurements were collected with atmospherically vented, recording pressure transducers (In-Situ, Inc. model Troll SP-4000 and SP-8000), 15psi models with manufacturer reported accuracy of $\pm 0.05\%$ full scale ($\pm 5\text{mm}$).

I calibrated transducers to reference benchmarks on the deployment structure that were separately surveyed topographically to benchmarks on the levees (see Topographic Surveys in Section 4.2.2 below). Calibrations consist of synoptic water level readings of the instrument and the reference elevation. I made multiple calibrations over the research period.

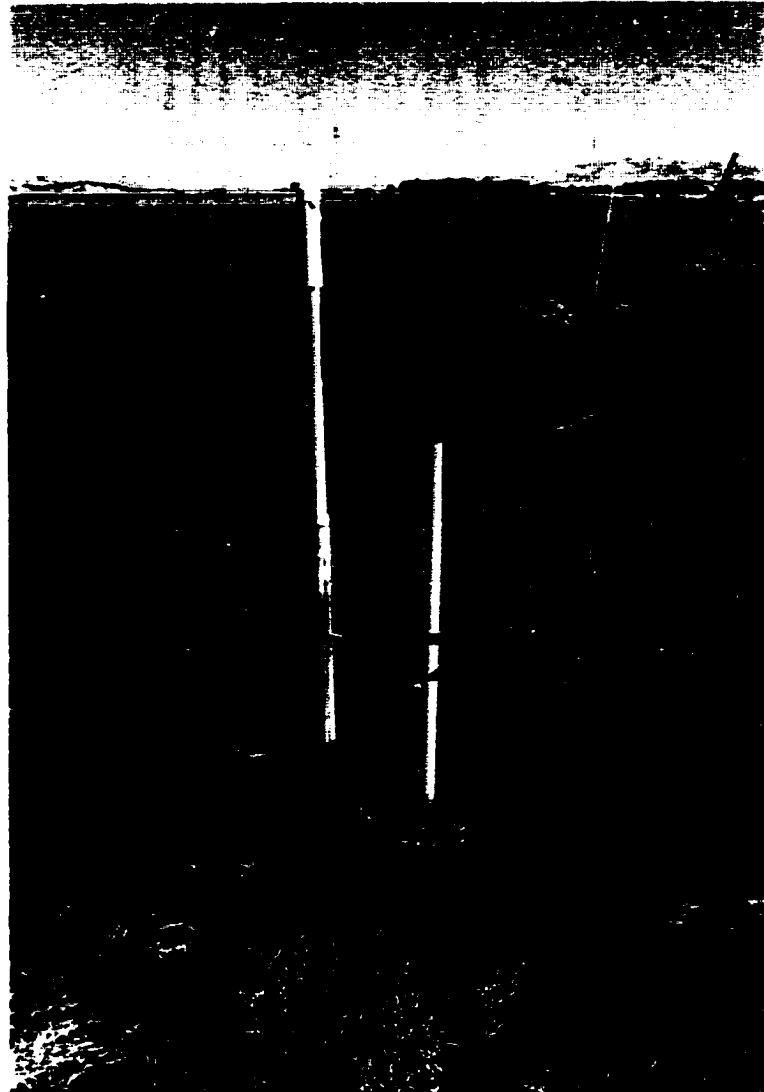
Photo 4-2 shows the different instrument deployment method at the North Breach station. At this station, the stilling well is attached to a single piece of steel angle iron.

Water level recording occurred at 12-minute intervals for the study period. This frequency allows for overlay with National Ocean Service continuous recording stations in the San Francisco Estuary (which operate at 6-min intervals) at a sufficient frequency to capture tidal peaks while minimizing data quantity.

4.1.2 Suspended Sediment Concentration

I measured suspended sediment concentration (SSC) with optical backscatter sensors (OBS; Downing Associates model OBS-3) connected to an external DC power supply and data logger. I measured SSC at four locations during the research: SC; SM; NC; and Upper South Channel (USC; located higher in the water column at the SC station) (Map 4-1). I used two instruments and moved them between stations.

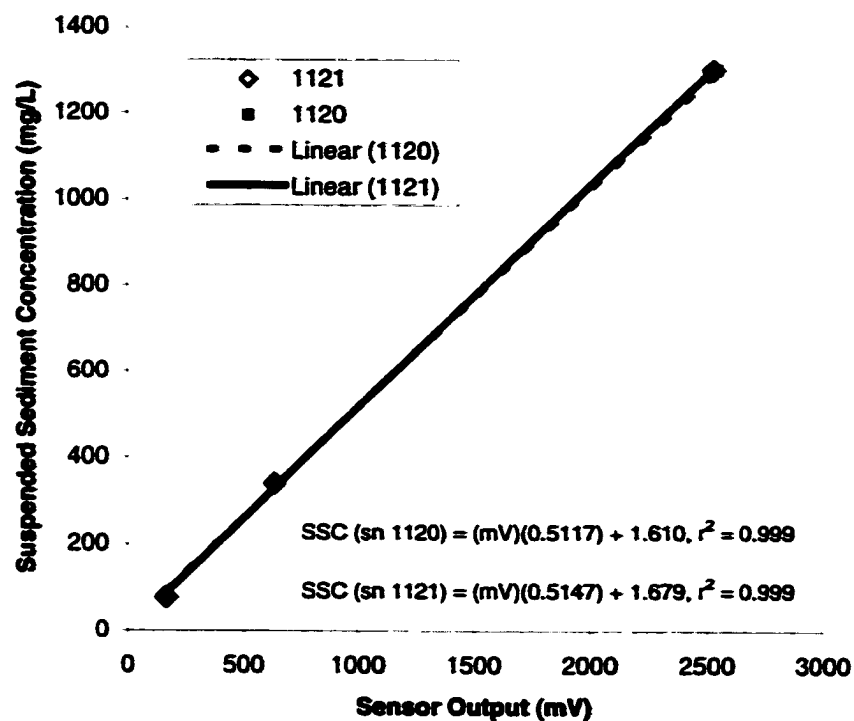
Photo 4-2. Transducer Deployment at North Breach Station



I calibrated the OBS sensors in the laboratory at the outset and conclusion of the research. Calibrations consisted of using water and sediment from the site in three concentration mixtures (low, medium, and high), recording sensor output at each concentration, and removing a sample from each concentration for commercial

laboratory analysis of suspended sediment concentration. From these data I then generated calibration curves and equations for each instrument to convert raw millivolt output to SSC (Figure 4-1). Other researchers have determined these instruments to have a linear response across a broad range of concentrations when measuring the fine-grained silts and clays commonly in suspension in the lower San Francisco Estuary (Shoellhamer and Buchanan 1998).

Figure 4-1. Optical Backscatter Sensor Calibration Curves



This figure shows the calibration data obtained for the two optical backscatter sensors used for this field study. Each sensor is denoted by its serial number (1120 and 1121), with the unique calibration equations shown on the graph used for converting sensor millivolt output into suspended sediment concentration.

I collected data at 12-minute intervals synoptic with water level. At each sample period, the instrument measured 64 samples at 1-second intervals and the data logger stored the average, minimum, maximum, and standard deviation of these 64 points. This burst strategy allowed reliable measurements to be made within the context of high frequency, low magnitude variations in heterogeneous water column SSC.

4.1.3 Velocity and Bed Elevation

I measured 3-dimensional velocity and bed level elevations with acoustic doppler velocimeters (ADV; Sontek model ADVField-10MHz) with integrated data logging connected to an external DC power supply. I measured velocity and bed elevation at four locations during the research: SC; SM; NC; and Upper South Channel (USC; located higher in the water column at the SC station) (Map 4-1). I used two instruments and moved them between stations. The ADV sensors are factory calibrated and according to the manufacturer require no periodic calibration.

I collected data at 12- or 15-minute intervals depending on the deployment. At each sample interval, two separate bursts were recorded: average velocity (0.5 Hz) and turbulent velocity (25 Hz) for durations ranging from 1-2min. Power supply and data logging limitations weighed heavily into the sampling strategy. Data quantity from each burst includes 3 dimensions (X, Y, and Z) multiplied by number of samples per burst (typically 24 for 0.5 Hz bursts and 1800-2400 for the 25 Hz bursts) plus a large number of automatically recorded data quality parameters. Instrument data loggers

were fitted with 40 megabyte cards, which could handle about one month of data recording with the selected burst strategy. I augmented power supplies with two 80-amp hour marine deep cycle batteries for each instrument to provide a secure power supply for each deployment.

4.1.4 Conductivity

I measured conductivity using electrical conductivity sensors (In-Situ, Inc. model Troll SP-8000) at two locations: SC and NB (see sampling locations in Map 4-1). I did not measure conductivity extensively due to continual sensor failure in the saline environment.

I calibrated the conductivity sensors in the laboratory at the outset and conclusion of each deployment. Calibrations consisted of conductivity standard solutions and software supplied by the instrument manufacturer that are used to measure reference conductivities and update internal sensor electronics. Instruments output calibrated conductivity values in units of milliSiemens cm^{-1} (mS cm^{-1}).

4.2 Periodic Field Measurements

Periodic field measurements consisted of measuring sediment pins, topographic surveys, grain size analysis, and sediment coring. Table 4-1 shows the times when these measurements were made.

4.2.1 Sediment Pins

Prior to opening the constructed site to tidal action in 1994, the California Department of Fish and Game placed five sediment pins at the site and measured their initial heights. Each pin consisted of 1-inch schedule 40 PVC pipe placed into the ground surface to resistance. I added another 14 sediment pins in early 1998, consisting of more rigid 2-inch schedule 40 PVC pipe. Sampling consists of measuring the distance from top of the sediment pin to the ground surface using a standard surveying stadia rod from a boat during high tide. The difference in readings over time is the elevation change at that location. Dividing those vertical measurements by time between the measurements yields sedimentation rates. The soft bottom sediments onto which the stadia rod is placed to measure pin height is difficult to determine the precise vertical position by feel with the stadia rod during measurement. Consequently, this method has an uncertainty estimated from field experience to be 2-3cm.

4.2.2 Topographic Surveys

I field surveyed topography at roughly 6-month intervals coincident with aerial photography (Table 4-1). Surveys were performed using a TopCon laser total station (model varied according to day). Areas surveyed included the reference benchmark at the nearby Highway 37 bridge, the 17 air photo control points, each levee breach, two cross sections in the South Basin pilot channel, and benchmarks on the instrument deployment structures (see Map 4-1 for survey locations). I sought maximum survey accuracy with all surveys, aiming for closure no greater than 0.003m (3mm), often requiring repeat measurements. I reached this closure in nearly every survey. The air photo control point benchmarks (Table 4-2) provided the reference benchmarks for site interior surveys.

Table 4-2. Air Photo Control Point Elevations and Locations

Point	<u>Location (SPC CA 3)¹</u>		<u>Elevation (NAVD)^{2,3}</u>					
	N (ft)	E (ft)	3/97 photo		9/96 photo		8/99 photo	
			(ft)	(m)	(ft)	(m)	(ft)	(m)
Inboard Levee			<u>17-Feb-97</u>		<u>17-Dec-98</u>		<u>10-Sep-99</u>	
Bridge			7.72	2.353				
AC 1	5,984,381.39	2,238,138.82	10.93	3.331	10.79	3.289	10.59	3.228
AC 2	5,984,360.63	2,237,704.10	10.66	3.249	10.45	3.186	10.24	3.121
AC 3	5,984,411.87	2,237,335.96	10.36	3.158	9.91	3.021	9.74	2.970
AC 4	5,984,995.82	2,237,160.32	11.12	3.389	10.95	3.338	10.79	3.288
AC 5	5,984,810.47	2,236,335.51	11.30	3.444	11.03	3.361	10.75	3.276
AC 6	5,984,945.35	2,236,033.97	11.36	3.462	10.99	3.350	10.78	3.286
AC 7	5,985,160.50	2,235,898.75	11.08	3.377	10.69	3.258	10.58	3.225
AC 15	5,983,944.33	2,238,316.93	na	na	8.85	2.698	8.78	2.676
AC 16	5,984,797.76	2,236,647.55	na	na	10.80	3.292	10.69	3.259
AC 17	5,984,141.64	2,238,728.10	na	na	7.70	2.348	7.67	2.336
Outboard Levee			<u>17-Feb-97</u>		<u>20-Nov-98</u>		<u>10-Sep-99</u>	
AC 8	5,984,713.81	2,235,530.46	7.11	2.167	7.15	2.180	7.11	2.168
AC 9	5,984,214.77	2,236,358.76	na	na	6.62	2.018	6.59	2.009
AC 10	5,984,410.41	2,235,985.84	6.72	2.048	6.75	2.058	6.72	2.047
AC 11	5,984,067.43	2,236,703.81	6.65	2.027	6.68	2.035	6.65	2.026
AC 12	5,983,945.62	2,237,029.38	6.64	2.024	6.67	2.032	6.63	2.019
AC 13	5,983,834.13	2,237,391.15	6.68	2.036	6.72	2.048	6.67	2.034
AC 14	5,983,739.51	2,237,735.47	6.62	2.018	6.64	2.024	6.59	2.007

Notes:

1. SPC CA 3 = State Plane Coordinates, California Zone 3. Relative position determined by Seher and Assoc. (CA-licensed surveyor); absolute position determined by Siegel.
2. February 1997 survey by Seher and Associates. All remaining surveys by Siegel.
3. Surveys performed with TopCon laser total station.

4.2.3 Sediment Grain Size Sampling and Analysis

I collected five shallow surface sediment samples (top 2 cm) for grain size analysis by the United States Geological Survey Western Coastal and Marine Geology Sediment Laboratory in Menlo Park, California. This small number of samples were collected based on field observations and expectations of relative uniformity in grain size character and thus little if any benefit could be gained by the cost of a larger sample

size. Two samples came from near the South Mudflat station, one from near the South Channel station, and two (including one replicate) from a short distance north of the South Channel station (see station locations on Map 4-1). Samples were collected with a 2-inch corer directly into plastic tubing then capped, sealed, and shipped to USGS for analysis. USGS followed analytical procedures modified from Carver (1971), Folk (1974), and Thiede *et al.* (1976). USGS utilized the Beckman Coulter LS100Q laser diffraction particle size analyzer for sediment finer than 0.063 mm (silt and clay) and settling tubes for the sand fraction (0.063 to 2 mm) (Torreson, personal communication).

4.2.4 Sediment Coring and Bulk Sediment Properties

In March 1997, students from the UC Berkeley Geography field course collected five cores and laboratory analyzed these cores for depth of accreted sediment, water content, percent organic matter, and bulk density. Cores were collected from a raft with a Livingston corer into plastic core tubes, labeled top and bottom, sealed to preserve the samples, and refrigerated within 6 hours of collection. Sample locations were qualitatively mapped and no ground surface elevation measurements were collected at the sample locations.

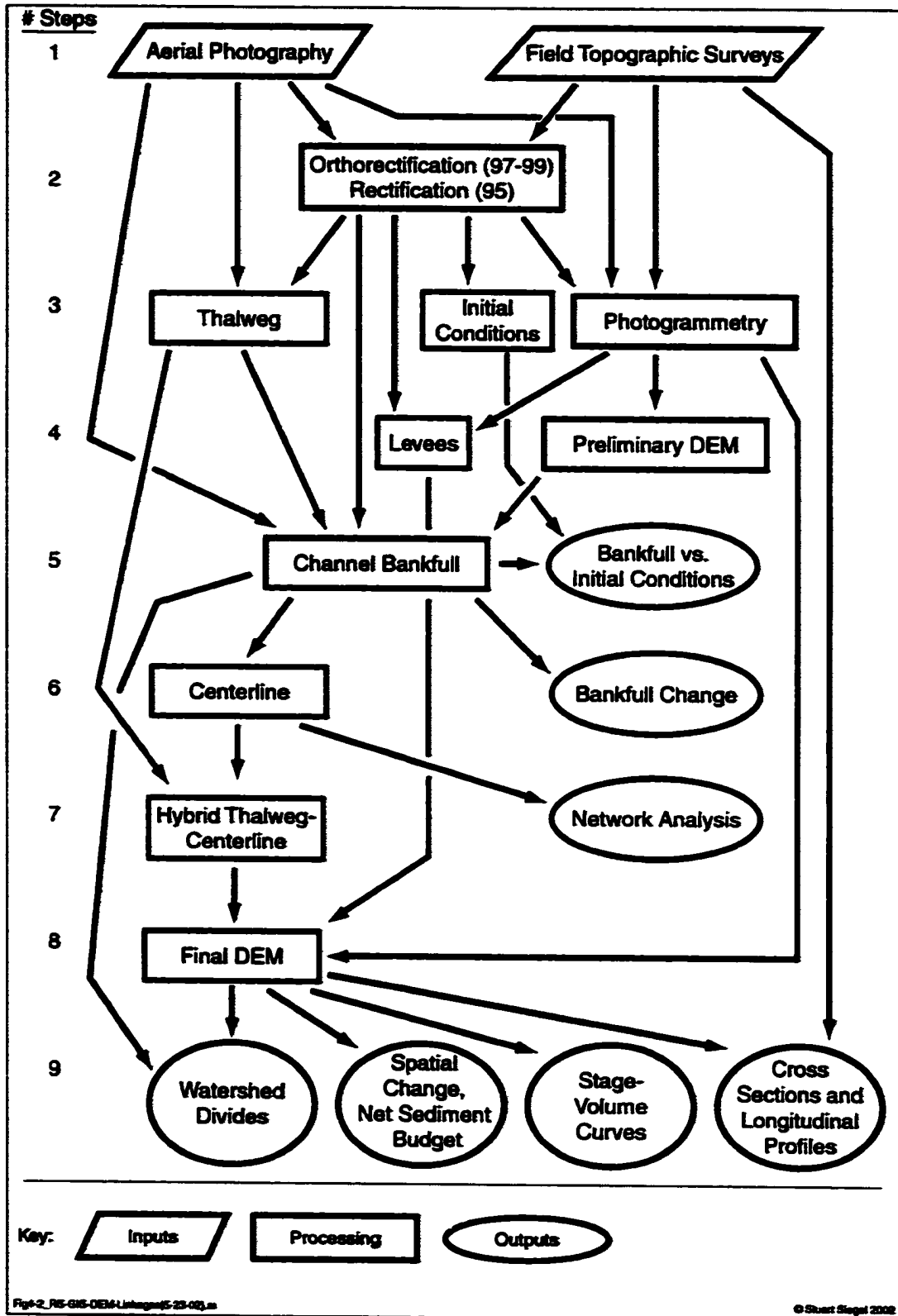
Accreted sediment depth was measured in the laboratory using a standard measuring tape, with the underlying farm field soils exhibiting a distinctive visual difference

from recently deposited fine-grained estuarine sediments. Water content was measured by extracting a subsample from the core and weighing it before and after drying for 24 hours at 100°C in a drying oven. Percent organic matter was measured by weighing the dried samples before and after combusting for 1 hour at 550°C. Bulk density was measured by extracting a quantitative sample volume from the core and weighing that sample.

4.3 Remote Sensing and Geographic Information Systems

This section describes the remote sensing and Geographic Information System (GIS) methods employed. Figure 4-2 illustrates the linkage between the data sets. Most of the data originate from three sets of low-altitude, stereo-pair aerial photography (March 1997, September 1998, and August 1999) combined with field topographic surveys to provide precision ground control for orthorectification, photogrammetry, and subsequent image analysis and GIS processing and analysis. In planning and applying these methods, a number of references were drawn upon, including Garbrecht and Martz (1996), Gurnell and Montgomery (1999), Helmlinger *et al.* (1993), Lyon (2001), Mason *et al.* (1997, 1998), Oertel (2001), Pilotti *et al.* (1996), Star *et al.* (1997), Walker and Willgoose (1999), and Wolf and Dewitt (2000).

Figure 4-2. Linkages in Data Methods



4.3.1 Aerial Photography

The basis for the geomorphic analysis rests upon time series, high-resolution, stereo-pair, orthorectified aerial photography. A total of five sets of photography were flown in this manner: March 1997, September 1997, April 1998, September 1998, and August 1999. I used three of these five photo series for the geomorphic analyses: first (March 1997), middle (September 1998), and last (August 1999).

Baseline Elevation Control

Vertical rectification is based on a single reference benchmark established for this research. The "Bridge Reference Benchmark" is a nail set into the concrete footing of the nearby bridge over the Petaluma River (see Map 4-1). This nail is set into a lead base inserted into a hole drilled into the bridge footing. I have made the assumption that the bridge footing is stable in the absence of seismic activity. I contracted with a licensed surveyor to install this benchmark and to establish its elevation with respect to the National Geodetical Vertical Datum of 1929 (NGVD) to a vertical accuracy of 0.01 ft (ref survey book). I have since updated this datum to the North American Vertical Datum of 1988 (NAVD) via tying into benchmarks recently surveyed by the National Geodetic Survey in the immediate vicinity of the site (NGS 1991).

Ground Control

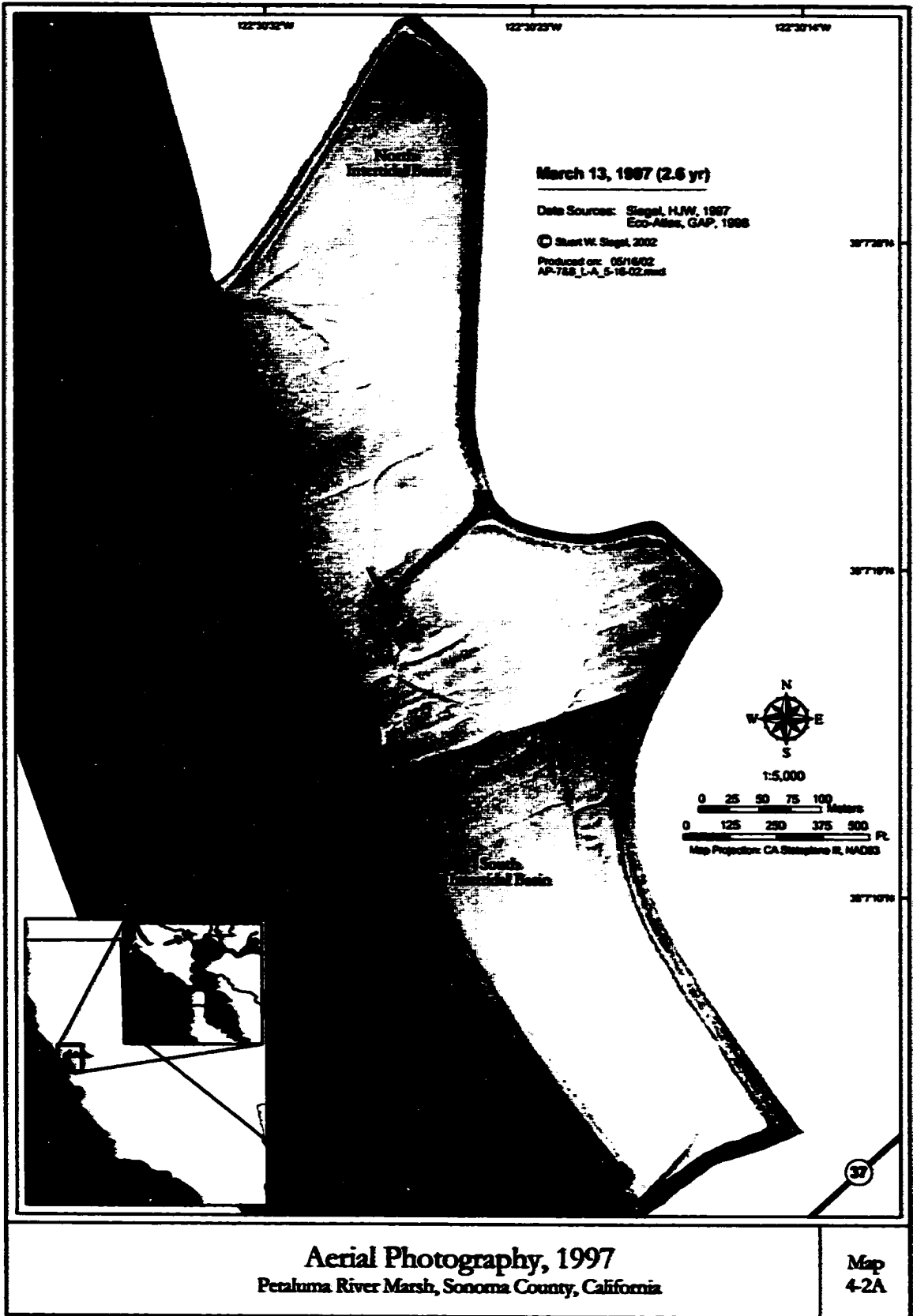
I installed a total of 17 ground control points on the inboard and outboard levees at the site (see Map 4-1). Each ground control point consists of an 18-inch (0.5-m) plastic stake pounded into the levee flush with the ground surface. At the outset of the

research program, the licensed surveyor surveyed these control points for vertical and horizontal position. Prior to each flight, I placed fresh white air photo markers (6 to 12 inches (15 to 30 cm) wide) onto the ground with the control point centered in these markers. I then resurveyed these control points to the Bridge Reference Benchmark concurrent with each new round of aerial photography in order to establish updated vertical control for orthorectification.

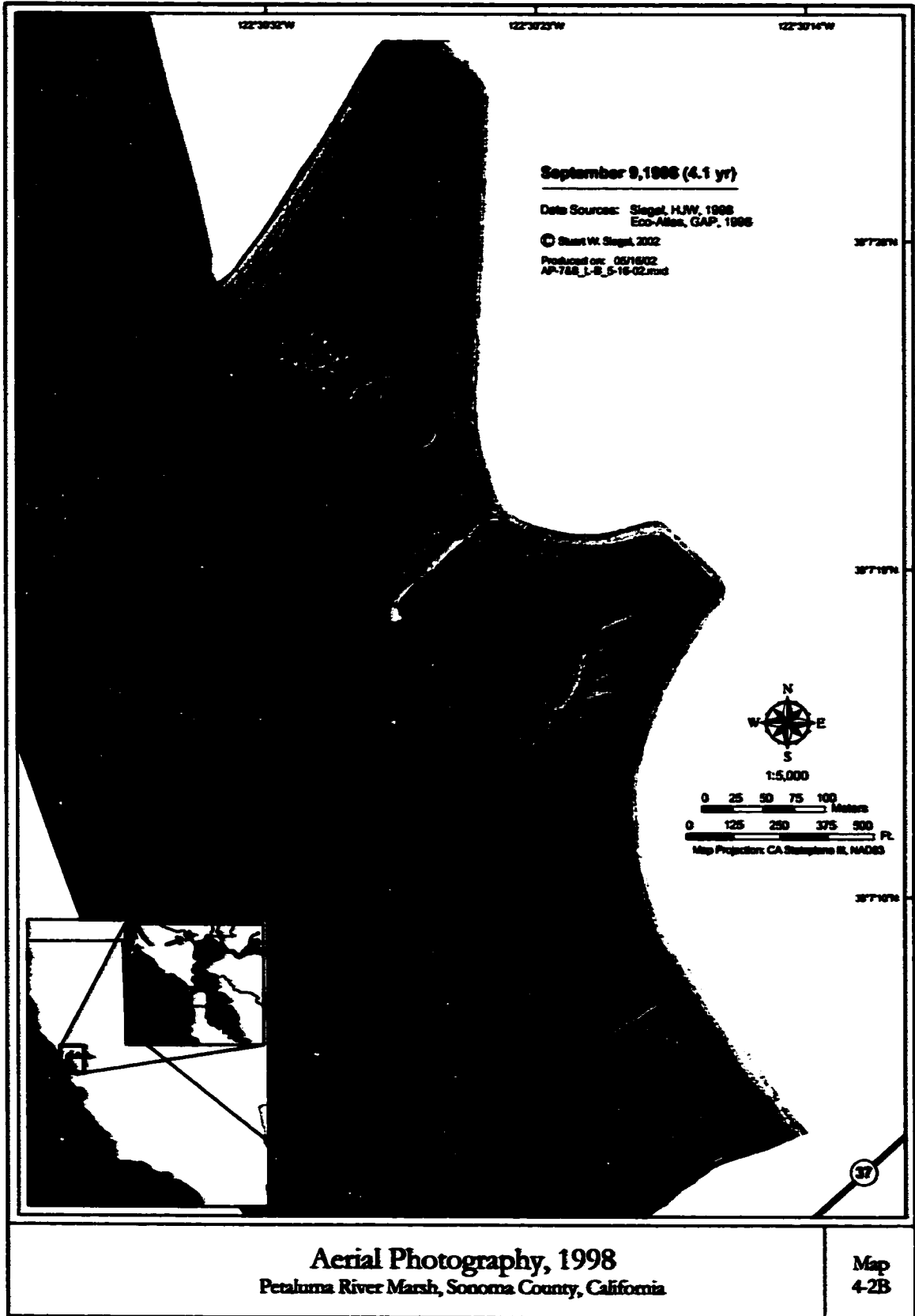
Flights

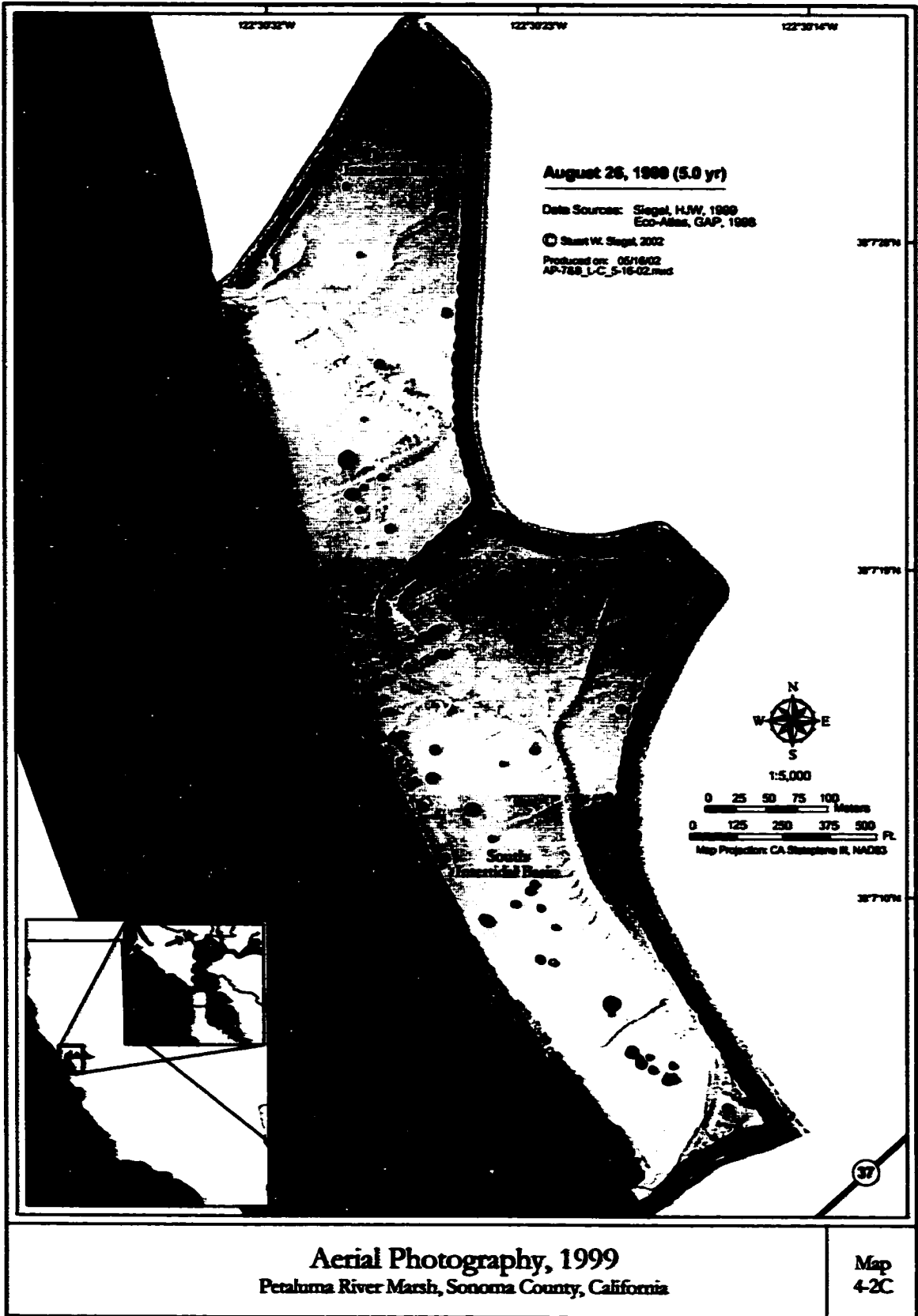
I contracted with Hammon, Jensen, Wallen (HJW), a local and long-established commercial aerial photography vendor, to fly each photo series. HJW used state-of-the-art 9x9 format cameras with calibrated 6-inch focal length lenses. Flight altitudes were approximately 1,000 ft, with photo scale approximately 1:2400. HJW used black and white film for three of the photo series (March 1997, September 1997, and April 1998) and color infrared film for the final two of the series (September 1998 and August 1999). I changed to infrared film for the latter two periods because vegetation colonization had begun and color infrared photography is the optimal medium for monitoring wetland vegetation (Lyon 2001).

Map 4-2 shows the aerial photographs for March 1997, September 1998, and August 1999 used extensively in subsequent analyses. Map 4-3 shows a previous photograph (November 1995) used to locate two initial conditions (small berms, pilot channels) as well as two photographs subsequent to completion of this research (September 2000 and August 2001) that facilitate understanding longer term conditions at the site.

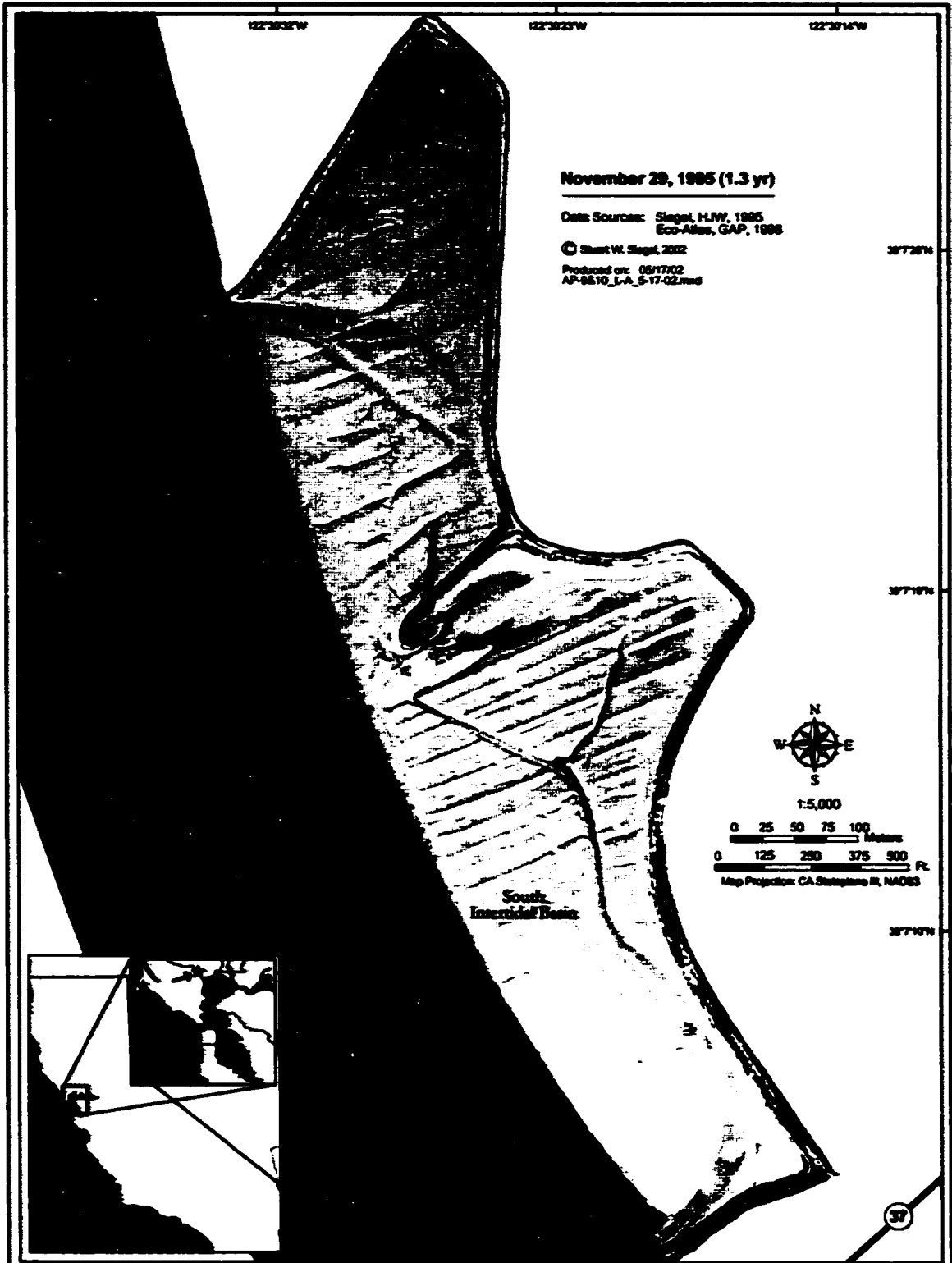


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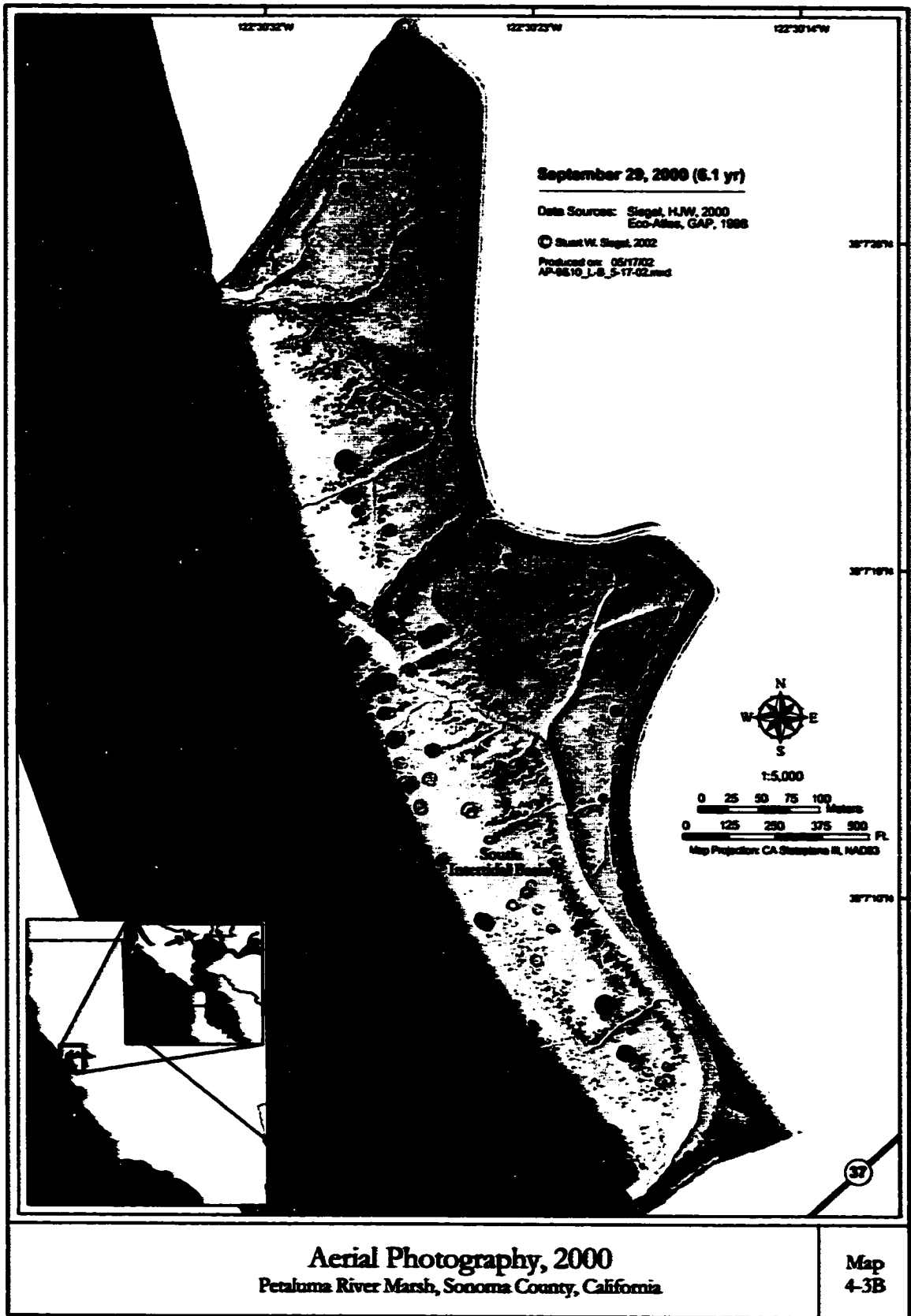


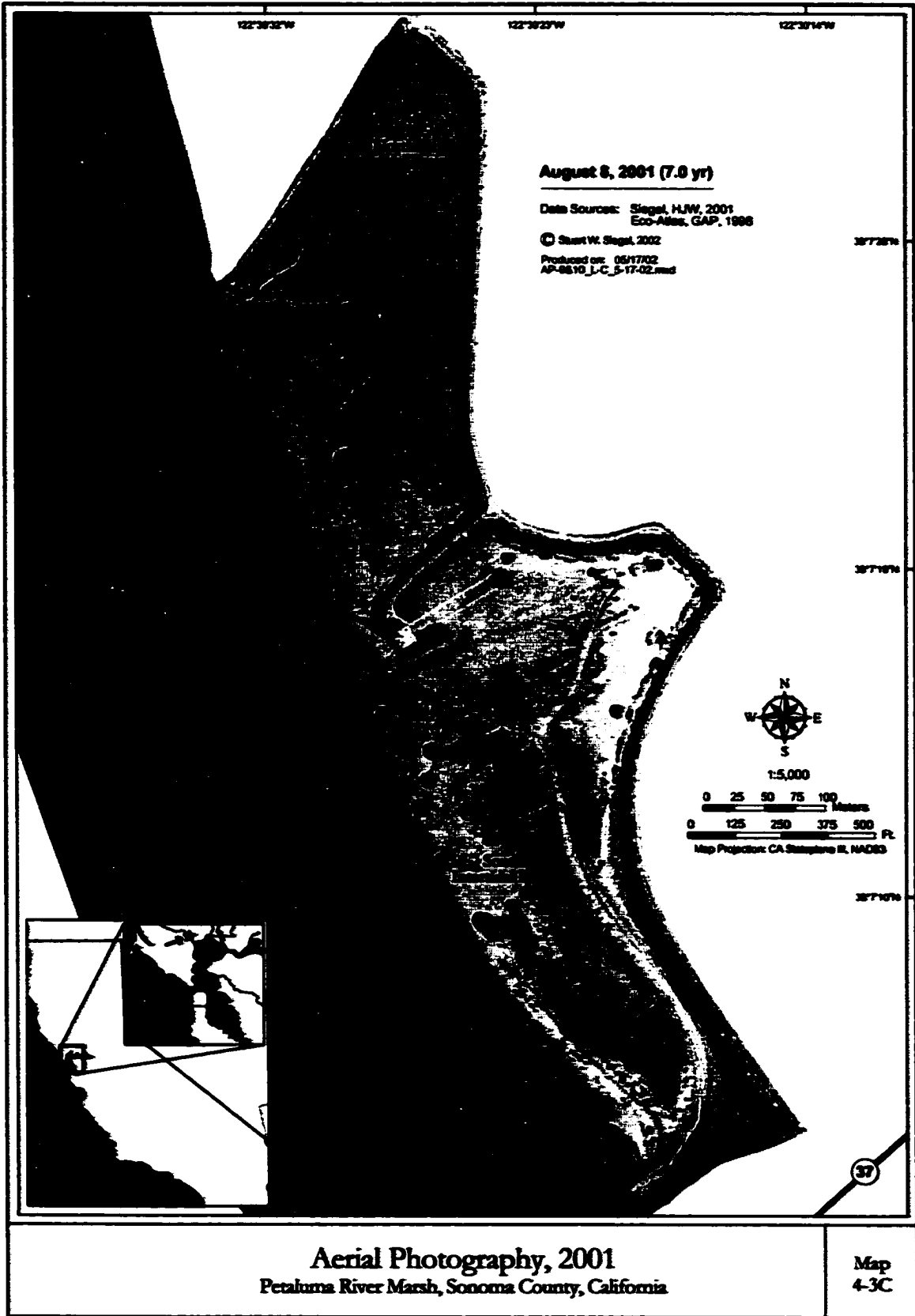
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Aerial Photography, 1995
Petaluma River Marsh, Sonoma County, California

Map
4-3A



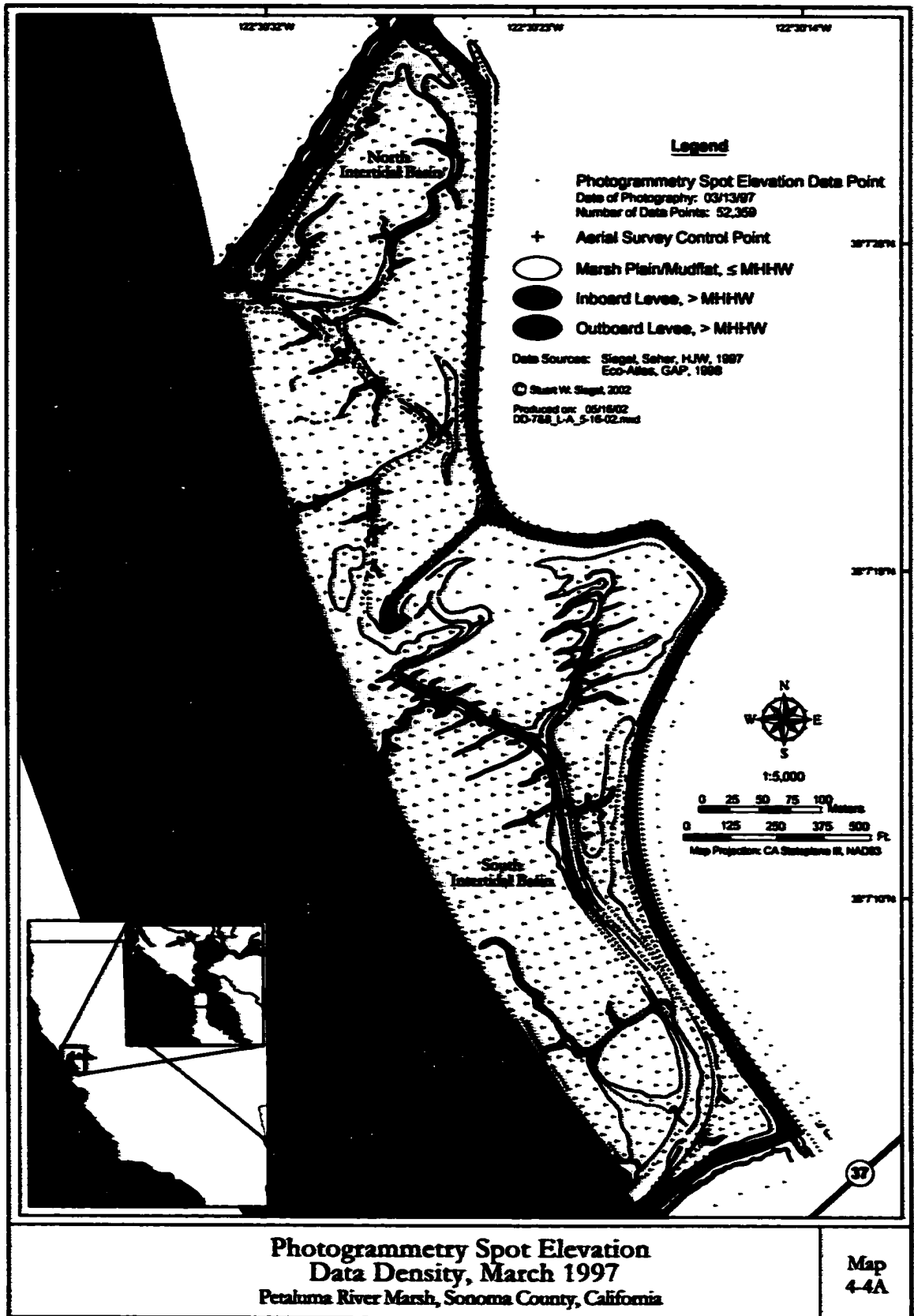


Orthorectification

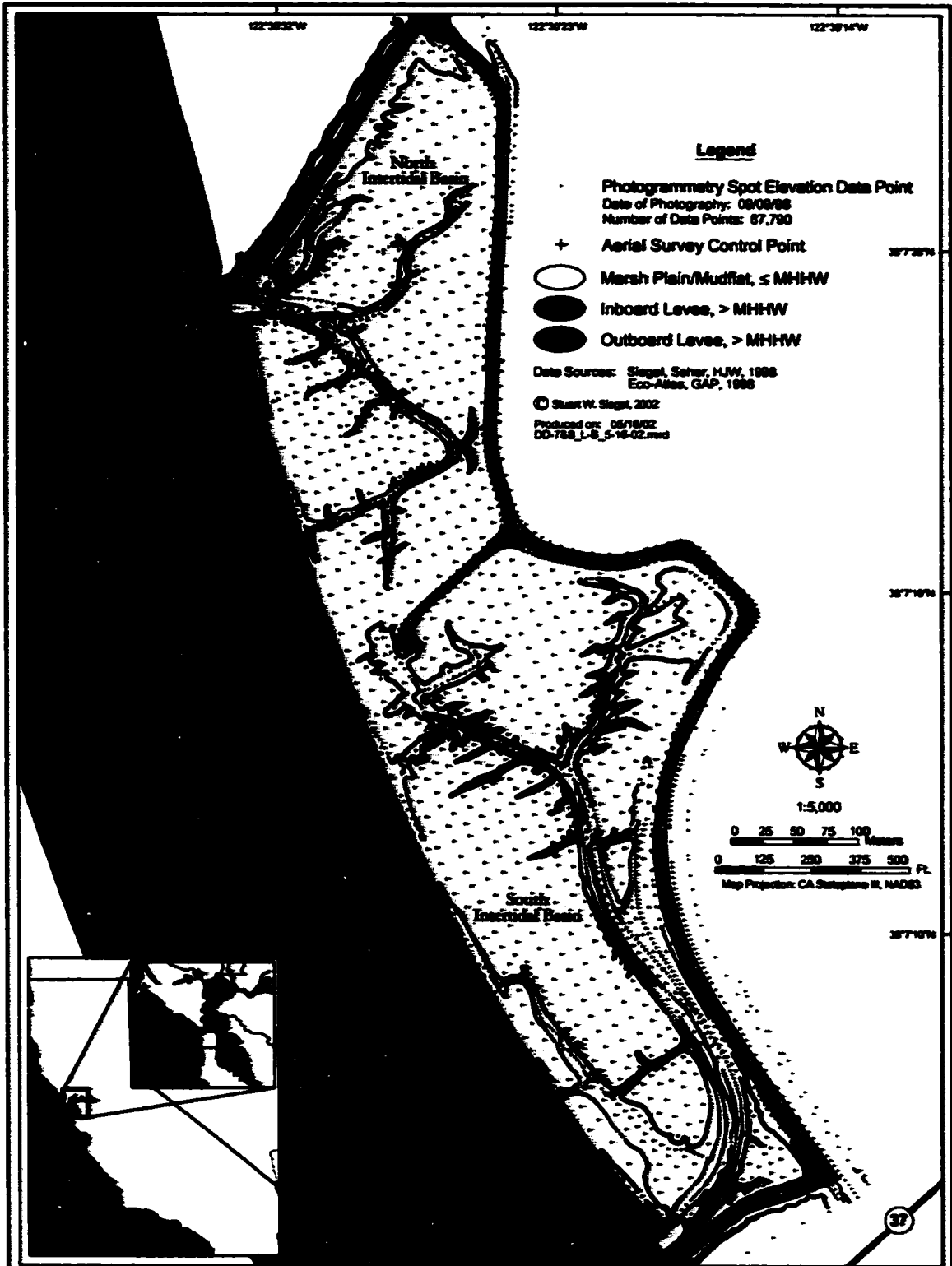
I contracted with HJW to orthorectify these photographs based on the 17 ground control points using orthorectification procedures standard for engineering photogrammetry (Hacker, pers. comm. 1999; Wolf and DeWitt 2000). HJW scanned the files at high resolution, leading to final products with a 0.17-ft (5.2-cm) pixel dimension.

4.3.2 Photogrammetry

I contracted with HJW to perform all photogrammetry. HJW utilizes analytical stereo plotters (Wolf and DeWitt 2000) in which film diapositives of stereo-pair photography are utilized. The photogrammetrist uses hand- and foot-operated controls to align points in the horizontal and vertical and digitally stores these points during the process. HJW used an uneven data density approach, in which high-density data are obtained for areas of topographic change such as along channel and levee banks and low-density data are obtained for areas of little topographic change such as on the marsh plain/mudflat surface. Map 4-4 shows the data density for the 1997, 1998, and 1999 data sets. HJW provided two data outputs from this process: spot elevations (eastings, northings, elevation) and contour lines generated by their software. All these data were used subsequently.

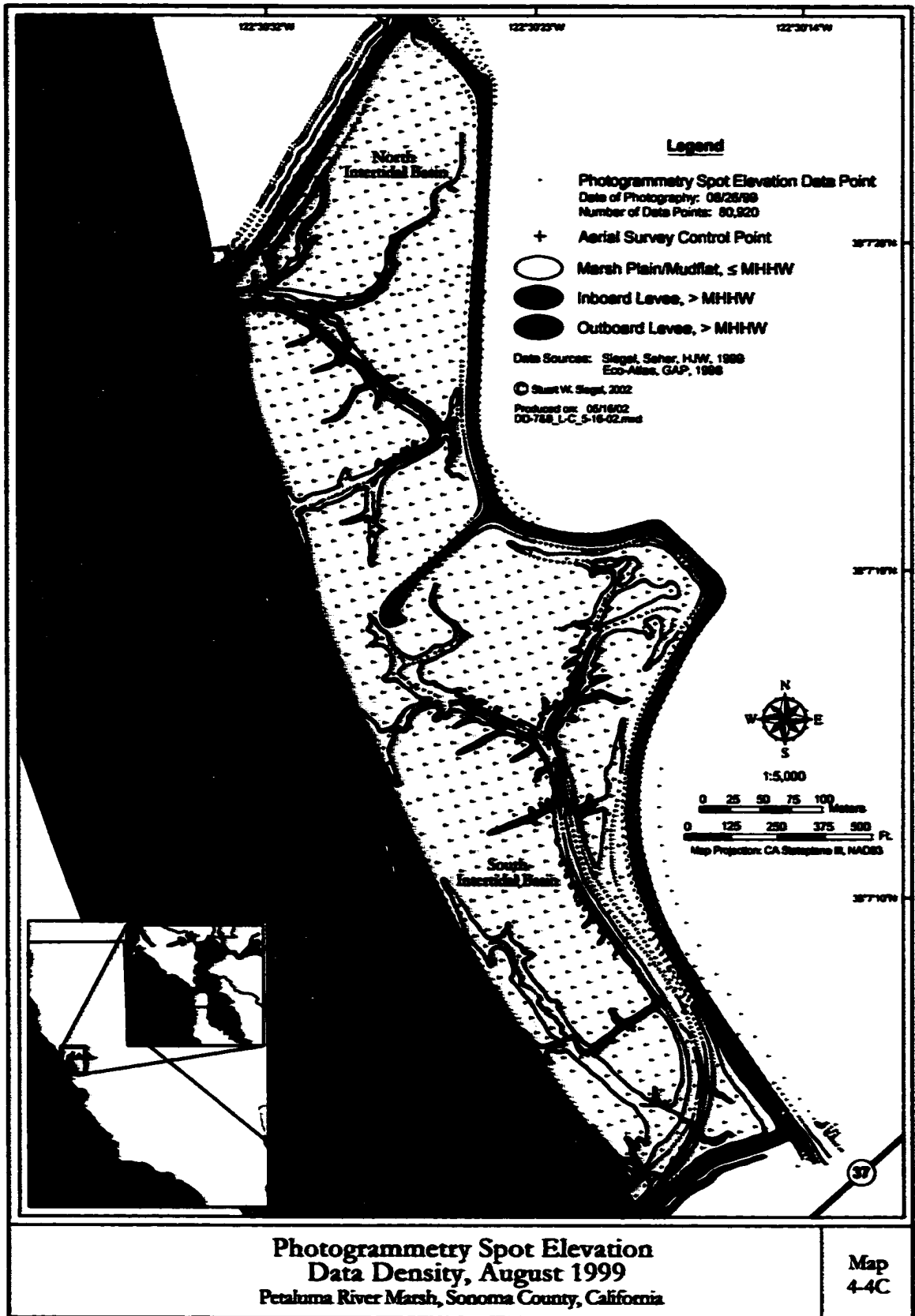


**Photogrammetry Spot Elevation
Data Density, March 1997**
Petaluma River Marsh, Sonoma County, California



**Photogrammetry Spot Elevation
Data Density, September 1998**
Petaluma River Marsh, Sonoma County, California

Map
4-4B



4.3.3 Preliminary Digital Elevation Model

I developed and used a preliminary digital elevation model (DEM) for the purpose of helping to establish channel bankfull locations in conjunction with orthorectified aerial imagery. The final DEM was developed using additional data, including the channel bankfull. I used the TOPOGRID routine in ArcInfo® to generate the preliminary DEM. Input data included the spot elevation and contours derived photogrammetrically by HJW (see Section 4.3.2). The contours served as hard breaklines to help establish channel and levee boundaries effectively.

4.3.4 Channel Bankfull Delineation

The next step in the analytical process was to delineate channel bankfull. Channel bankfull as used here has a topographic definition: the location at which the channel top of bank meets the marsh plain/mudflat surface. In effect, channel bankfull occurs at the break in slope between the marsh plain and channels.

Extracting the channel bankfull locations involves several steps. First, channels are grouped into two broad categories that I termed “primary” and “secondary.” Next, we used GIS tools to extract primary channel bankfull locations and manually digitized the secondary channel bankfull locations. The purpose in separating channels into two categories is to allow for scale consideration. This research collected very high

resolution aerial photography digitized to 0.052m (0.17ft) pixel dimensions from which quite small features can be extracted. Lower resolution imagery is commonly used for cost savings and data management purposes and such imagery typically does not allow for equal identification of features as used here. The primary channels therefore are intended to represent the larger channels that would be clearly definable with coarser aerial imagery.

Primary and Secondary Channels Defined

Primary channels encompass most of the channels on the site. I have defined primary channels as those channels that (1) have a thalweg (low flow channel) that is visible in the high-resolution aerial photography and continues to a levee breach, (2) are at least third order channels using the Strahler Order definition (Strahler 1964), and (3) are not small "rill" channels normal to the larger channels. In practice, primary channels are the medium and large channels that would be visible in lower resolution data.

Secondary channels constitute the large number of very small channels on the site. I have defined secondary channels as those channels that (1) do not have thalwegs continuous to either levee breach as visible in the aerial photography, and/or (2) are small first and second order channels typically normal to the larger primary channels. In practice, secondary channels are the smallest "rill" channels that are tributary to the medium and large primary channels. They are in the size range of 0.3 to 0.6 m (1 to 2 ft) wide, less than 0.3 m (1 ft) deep, typically though not always have a V-shaped cross section, and extend in length from roughly 1 to 10 m (3 to 30 ft). They tend to

occur at fairly high elevations along the upper edges of the primary channel banks, drain into the primary channels as hanging valleys, and only have flowing water at higher tide levels.

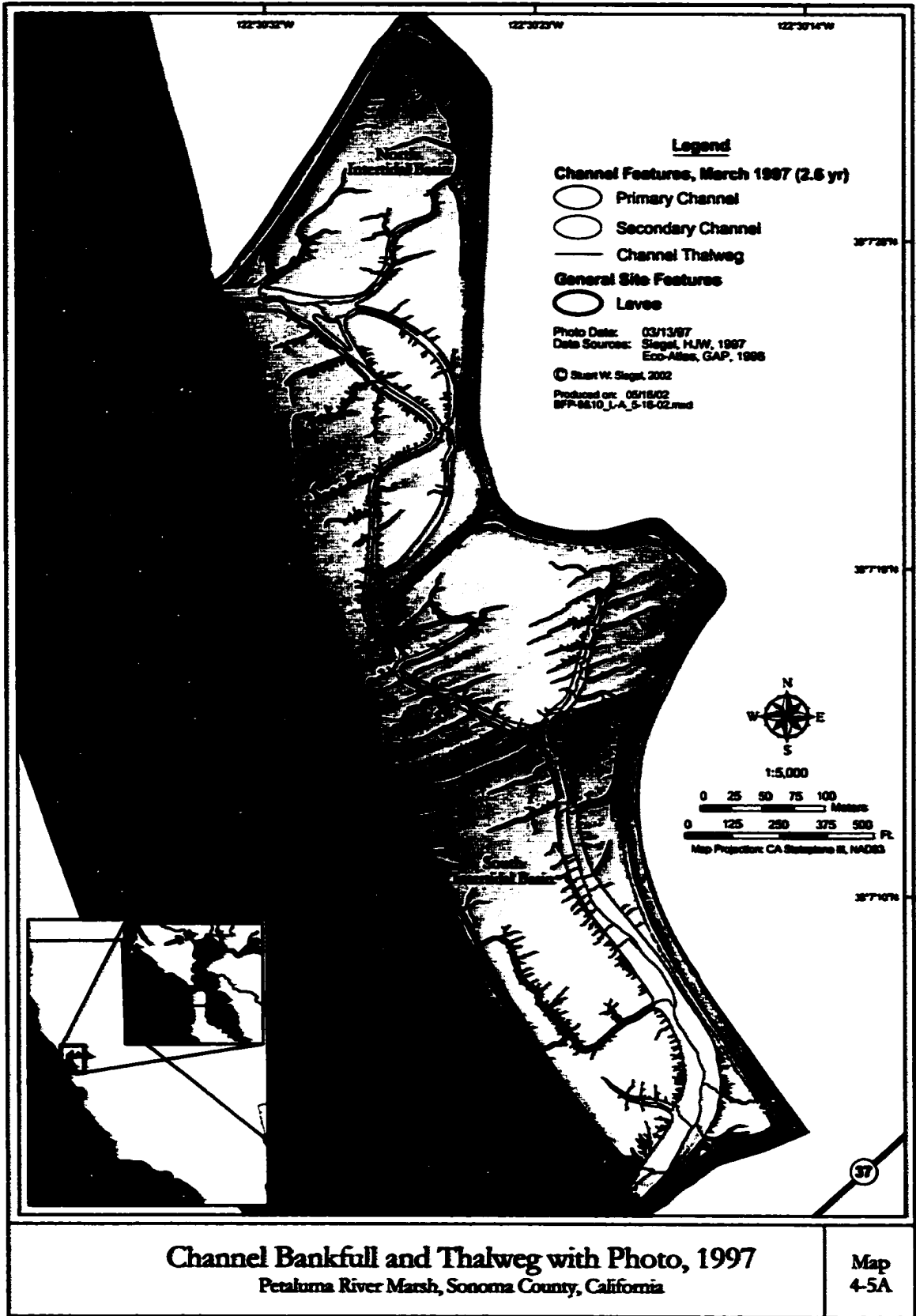
Establishing Primary Channel Bankfull Position

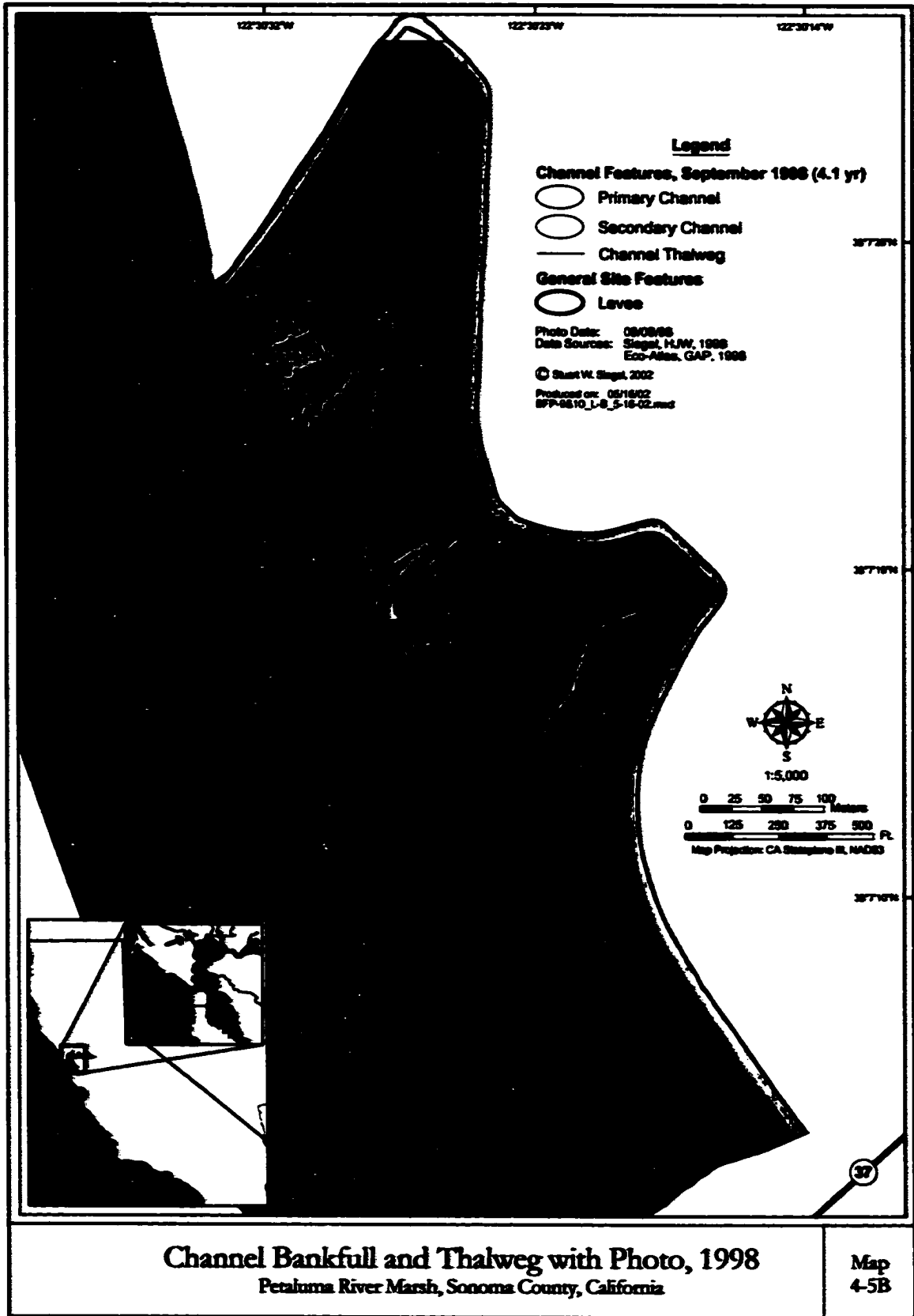
I used three data sources to establish the primary channel bankfull position: preliminary DEM-generated contour lines (0.1-ft interval), preliminary DEM-generated slope maps, and orthorectified aerial photography (Map 4-2). From these three data sources I identified the appropriate lines (contour intervals) that best represented bankfull location. I selected lines based on a combination of examining contour density, slope maps, and air photo features. I selected individual contour arcs across the entire site using this protocol, which allowed for topographic variability in actual bankfull consistent with how the marsh plain/mudflat surface of the site “sloped” away from the levee breaches. The contour lines in effect offered a convenient automated line for conversion into the bankfull coverage. In places where the contour lines did not yield a satisfactory bankfull location, I digitized a new line manually. I performed all this work in ArcInfo®.

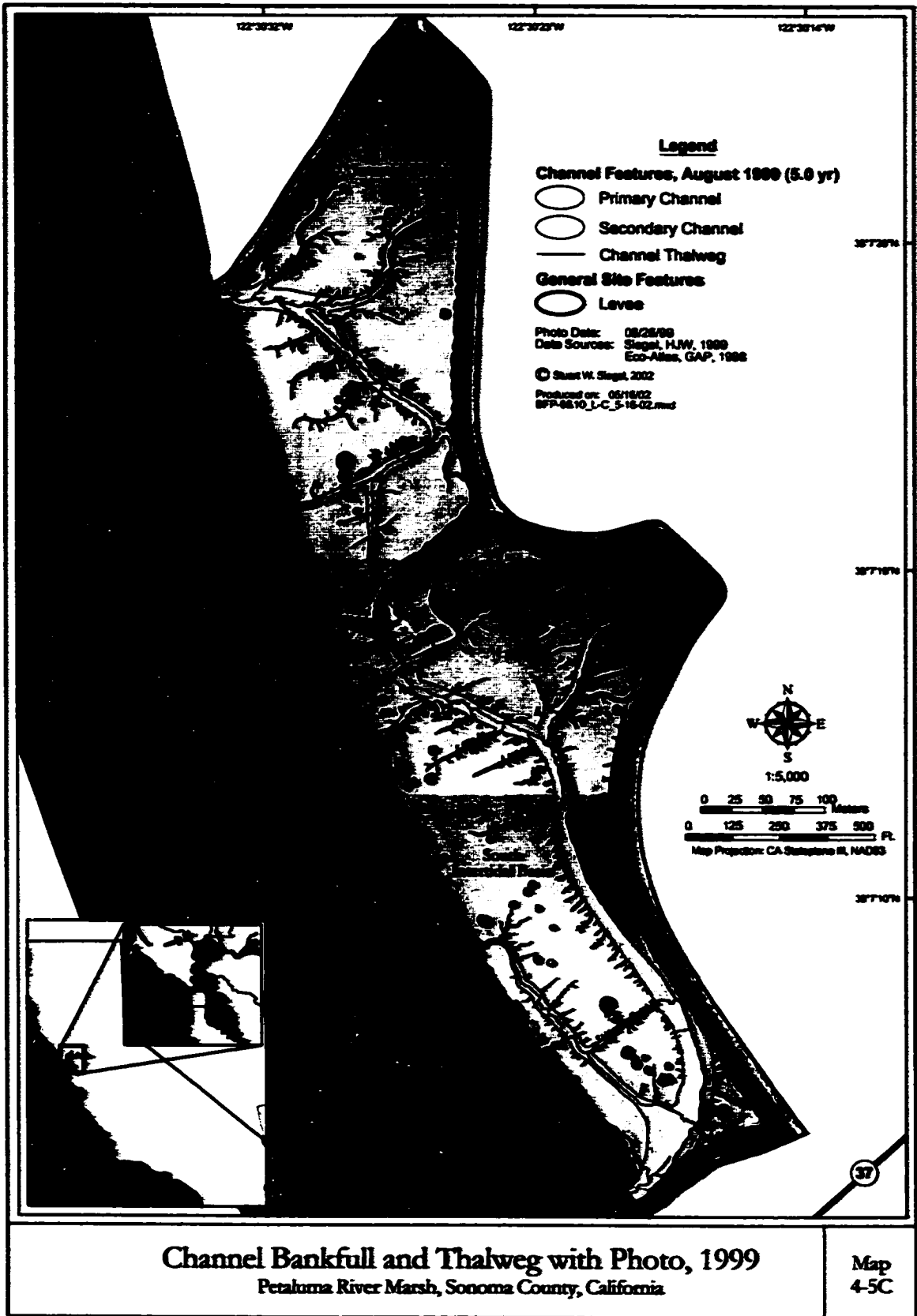
Establishing Secondary Channel Bankfull Position

I digitized secondary channels entirely manually on screen from the high-resolution (0.17-ft/5.2-cm pixel size) orthorectified aerial photography.

Channel bankfull locations for each year of aerial photography and DEM are shown in Map 4-5.







4.3.5 Channel Thalweg Delineation

I digitized channel thalwegs entirely manually on screen from the high-resolution (0.17-ft/5.2-cm pixel size) orthorectified aerial photography. Thalweg locations are shown in Map 4-5.

4.3.6 Channel Centerline Delineation

Channel centerline serves as the basis for all the network analyses and thus is important to generate comprehensively. I had to generate a variety of centerline coverages specific to each intended use; all coverages are based on the centerline coverage derived from the channel bankfull shown in Map 4-5. These coverages include the “full” centerline coverage, the “network analysis” centerline coverage which adjusted the full centerline to function within a fluvial geomorphic analytic framework, and a hybrid coverage mixing secondary centerlines with thalwegs to support the final DEM generation. Finally, I present the methodology used to calculate centerline length.

Centerlines Derived from Bankfull Coverage

The full centerline coverage differs in two important ways from that necessary for the analyses performed in this research. First, it includes looped (circular) channel features commonly found in tidal marsh systems but uncommon in fluvial systems (except in

braided streams and deltaic environments). Second, it did not connect the centerlines of the small secondary channels directly to the centerline of the larger primary channels. In practice, secondary channels only carry water during higher tides, so a gap in the centerline reflects field conditions. Solutions for both these limitations are described below.

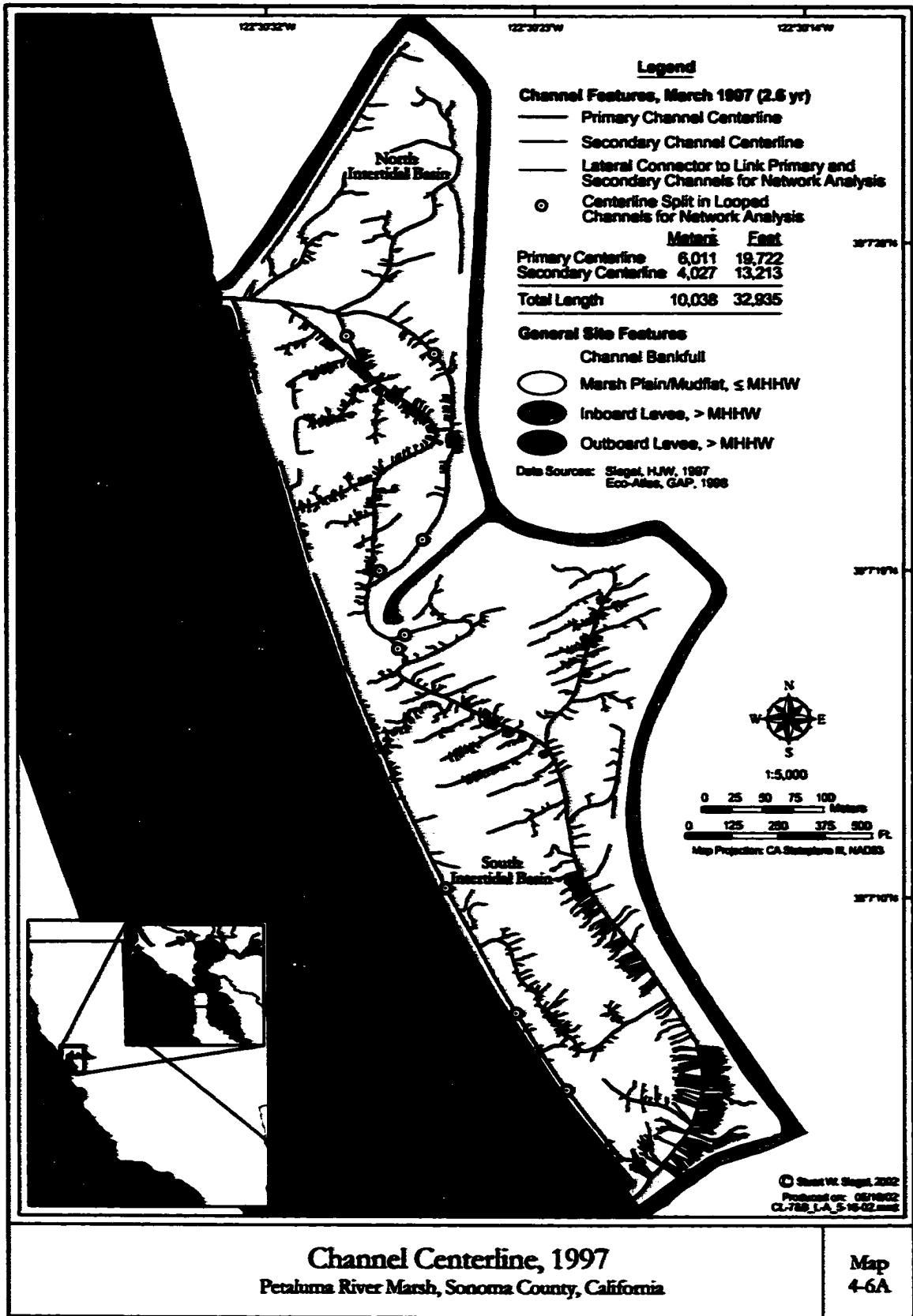
Generating the full centerline coverage combined automated and manual line generation. For the automated method, I selected arcs on both sides of a channel, then used the simple ArcInfo® “centerline” command (ESRI 2000). The manual method involved “indirect digitizing.” That is, instead of drawing a line down the middle, one clicks on either side of the channel to create one point, then again on opposite side of the channel further down for the next point, creating a centerline arc. How far down one clicks for the arc-generating second point depends entirely on channel sinuosity and variations in width for that section. To capture a smooth centerline of a curve, many short side clicks are required, but long jumps are possible in straighter sections, especially where the channel width is fairly consistent.

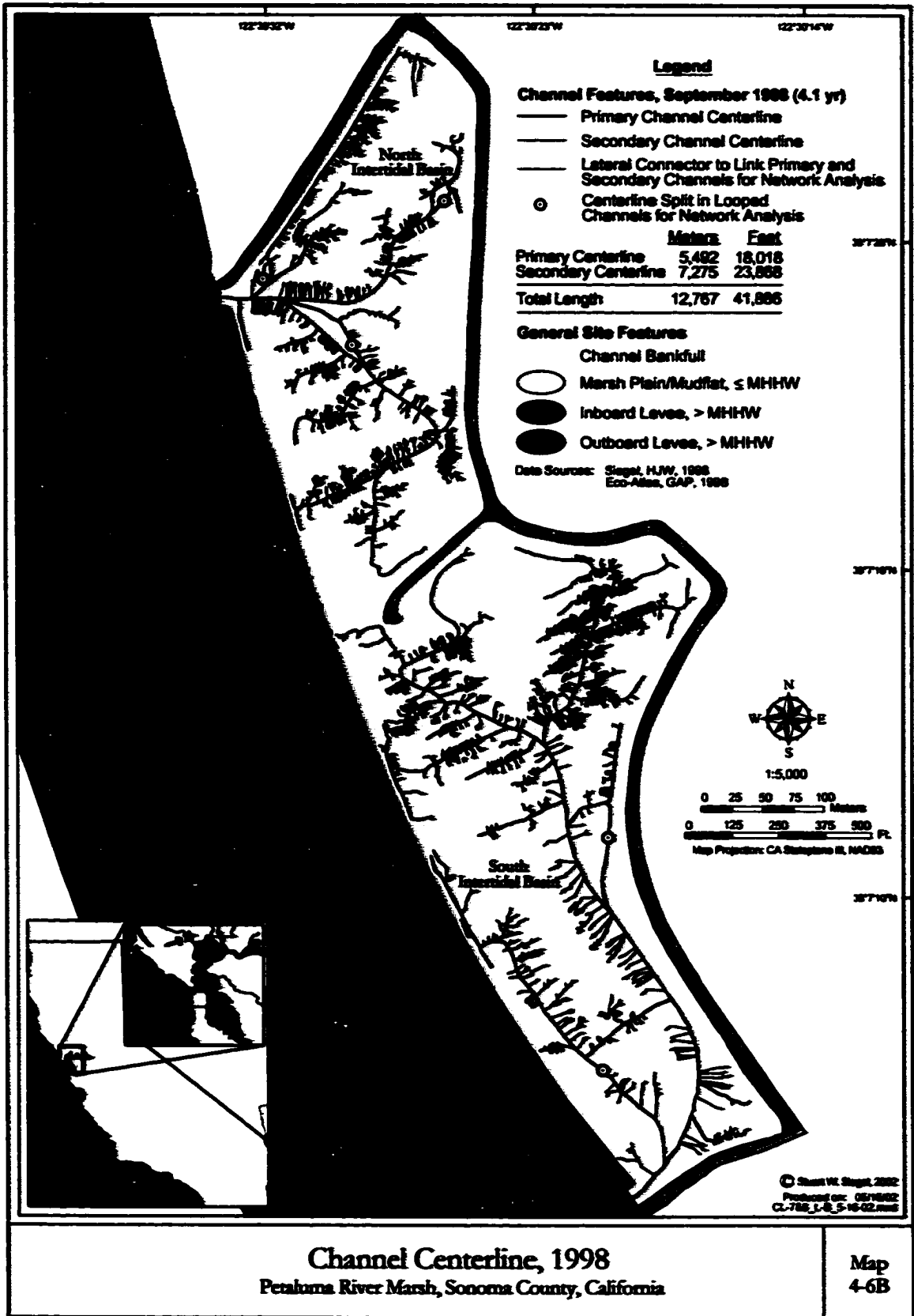
At channel junctions, this routine yielded results that did not represent a natural “flow path.” In these locations I manually edited the centerline coverage to create a more naturalistic “flow path” for ebb tide flow direction (corresponding to “downstream” in a fluvial geomorphic context).

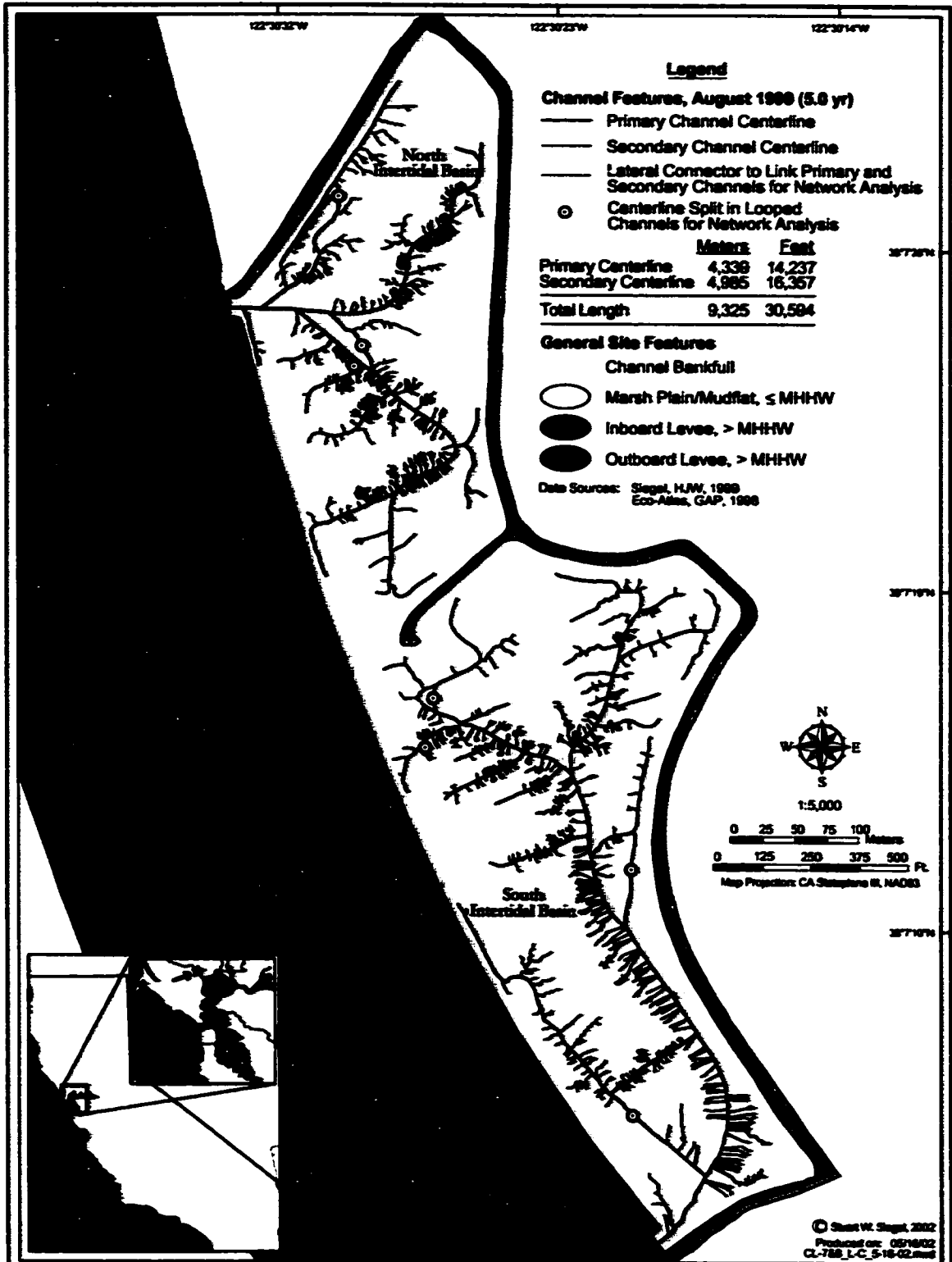
Centerlines Linked for Network Analysis

Next I used the centerline coverage as the basis to create a linked channel network coverage suitable for use in a network analysis of Strahler Order and Shreve Magnitude (see Section 4.3.7). A linked channel network is one in which there is a continuous flow line from every channel head to the trunk channel (the levee breaches in this case) (Strahler 1964). In tidal systems, this flow direction is ebb tide; in fluvial systems, it is downstream).

Two steps were necessary to generate this coverage from the centerline coverage: connecting the secondary channel centerlines to the primary channel centerlines in order to have a continuous flow routing coverage, and inserting breaks in looped channels so that every channel had an “upstream” (headward in tidal systems) end to it. Map 4-6 illustrates these modifications. As noted below, the “lateral connectors” artificially inserted for network connectivity purposes are not counted in channel centerline length calculations.







Channel Centerline, 1999
Petaluma River Marsh, Sonoma County, California

Map
4-6C

Lateral Connectors to Secondary Channels. The product of the centerline generation algorithm created a continuous coverage for the primary channels but it left most of the secondary channel centerlines disconnected from the primary channel centerlines. This outcome is desired, as a small secondary channel tributary to a large primary channel does not have flowing water except at higher tides and thus it should not have a real centerline down the banks of the larger primary channel. However, to conduct a channel network analysis, all channels must be connected into a single arc coverage. Therefore, I created lateral connectors to make this connection. These connectors are “artificial” centerlines and thus are used only in the network analysis; they are omitted from any other analyses such as measuring total centerline length.

Breaks in Loop Channels. Tidal systems commonly have channels that loop to form a circular connected channel. These conditions are typically not found in fluvial systems and since the channel network analysis tools derive exclusively from fluvial geomorphology, it is necessary to make the coverage conform to fluvial patterns. In practice, looped channels in tidal marsh systems always have a “flow divide” where tides will flow in opposite directions (e.g., Leopold and Collins 1993). Consequently, I inserted gaps in the centerline coverage in all loop channels at a location approximating the flow divides. For network analysis purposes, the precise location of the break makes no difference so long as it occurs within the same channel segment.

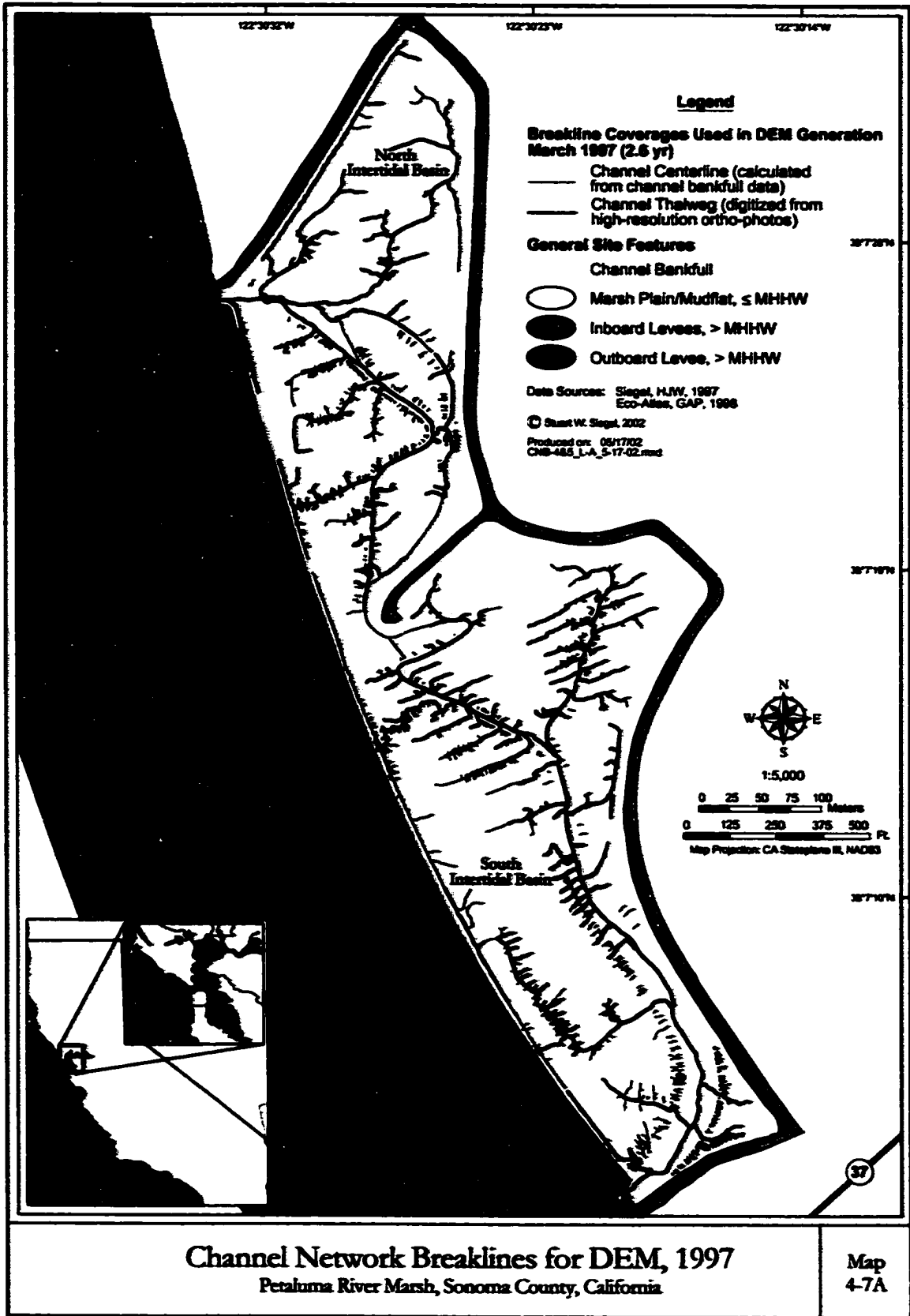
Hybrid Thalweg-Centerline DEM Breakline

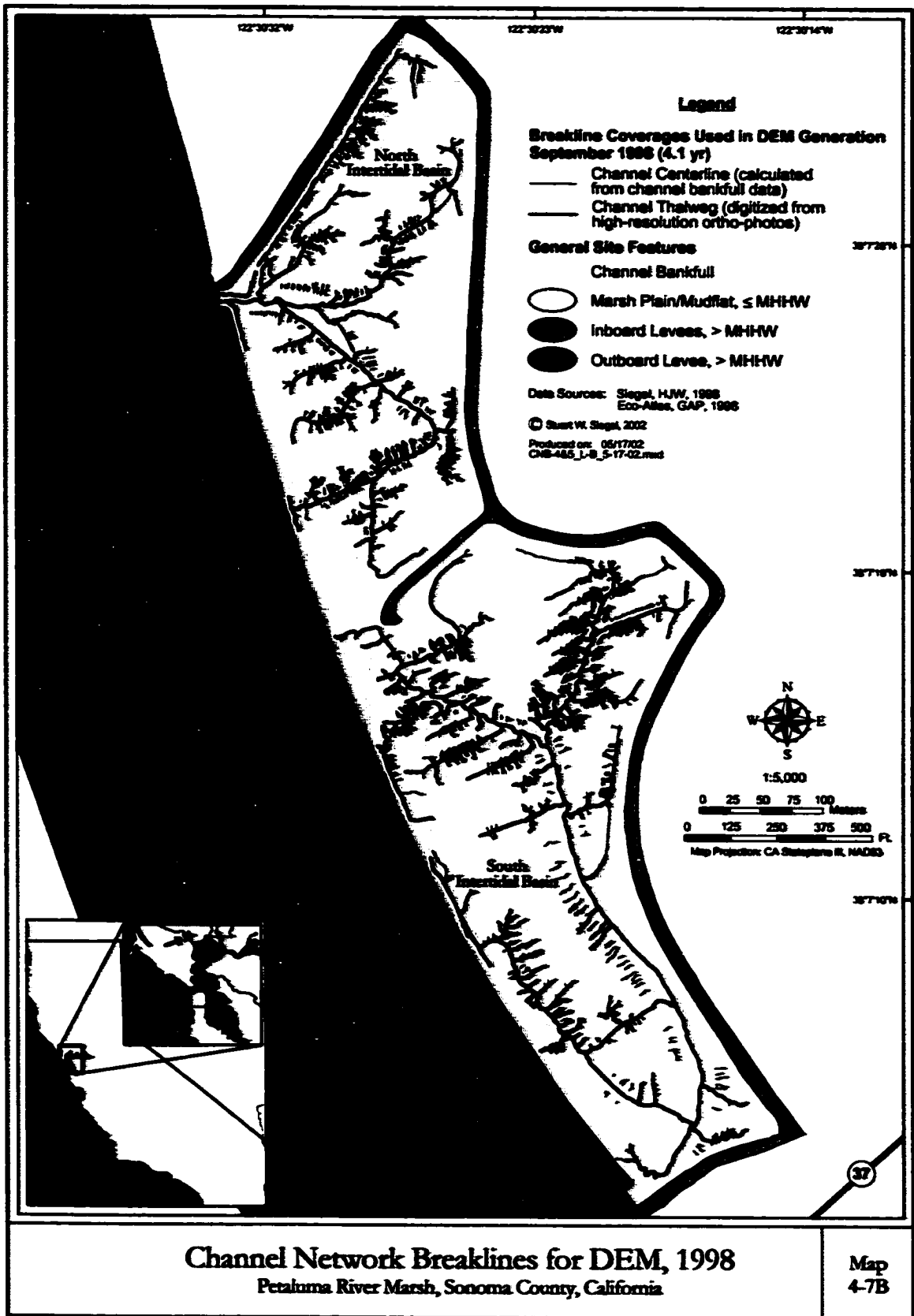
The third coverage created from the centerline data is the hybrid thalweg-centerline. Its purpose is to provide a complete “channel” breakline for generating the DEMs, representing “downhill” (bayward) channel flow. The optimal coverage would have a flow line for every single channel on the site.

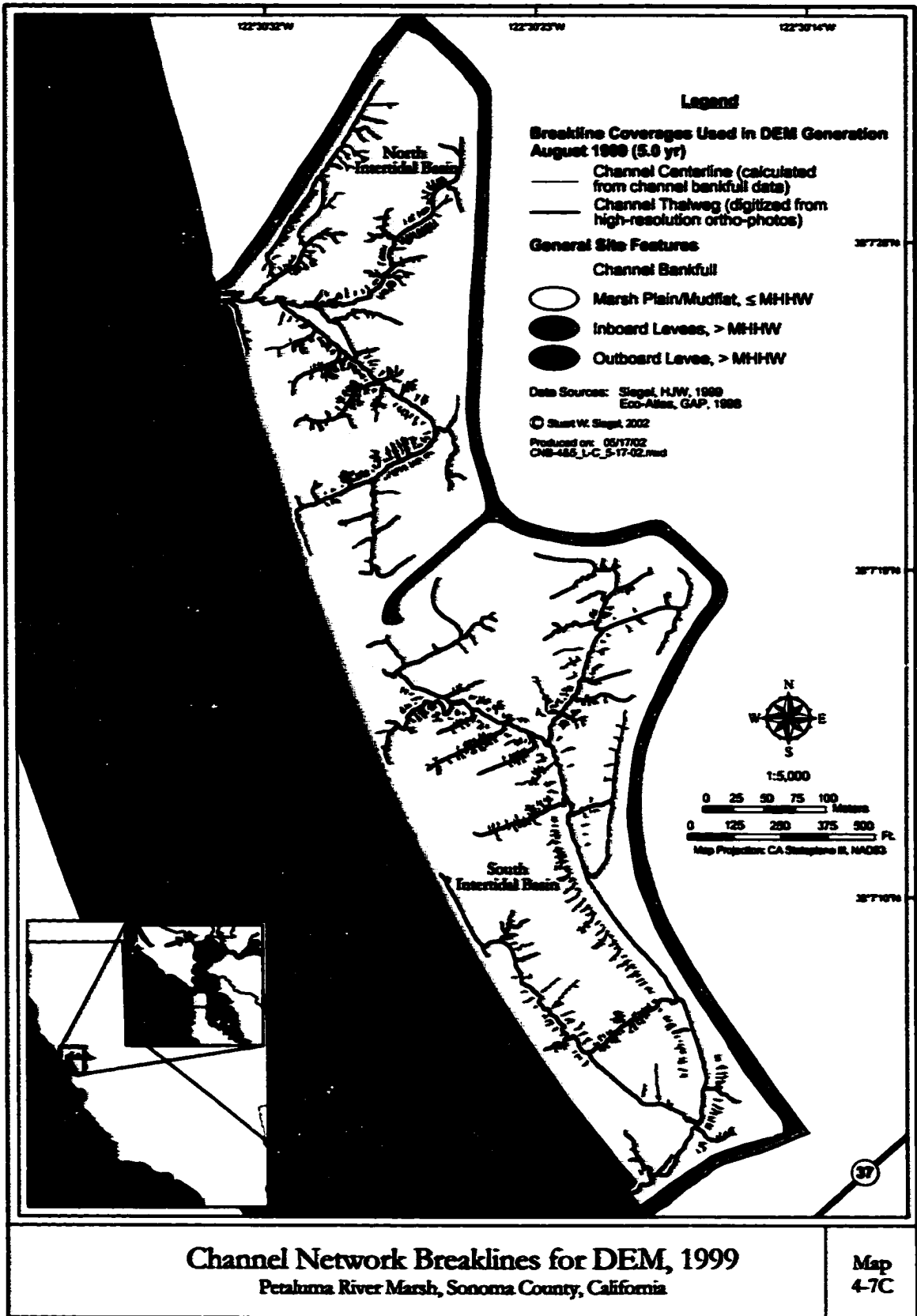
I generated the hybrid thalweg-centerline coverage specifically to provide this optimal breakline. The hybrid coverage consists of the entire thalweg coverage digitized from the orthorectified aerial photographs plus all arcs of the centerline coverage that do not overlap with the thalweg. This combination effectively extends a flow line to the headward reach of every single channel on the site. Map 4-7 illustrates this hybrid coverage.

Centerline Lengths

Once I had generated channel centerlines and a network coverage, channel centerline length could be determined for each data set. The centerline length includes all the centerlines in the final network and excludes all the “lateral connectors” used to generate a continuous network from the centerlines.







4.3.7 Network Analyses

I used the completed channel centerline network (Map 4-6) for extracting several channel network attributes for each of the three data sets: Strahler Order, Shreve Magnitude, channel density (area/area and length/area), and bifurcation ratio. All but Shreve magnitude data are commonly used in wetland restoration design for planning channel networks and thus are important design metrics. Shreve magnitude data help to evaluate temporal dynamics of the channel network.

Strahler Order and Shreve Magnitude

Strahler Order is a method that identifies the extent of branching in a channel network. Starting at the upstream (headward in a tidal system), channels are labeled “first order.” When two first order channels meet, the resultant channel is labeled “second order” (Strahler 1957, 1964). This method is carried throughout the channel network to its base location, which in this case is the levee breaches.

Shreve Magnitude is a method that identifies the number of first order channels in the system. Starting at the upstream end, every first order channel is given a numerical value of 1. As two first order channels merge, the resultant channel is given a value of 2. As another first order channel merges, the resultant channel is given a value of 3. As other higher-order channels merge, their respective values are added together. Thus, at the downstream end of the network (the levee breaches here), the Shreve Magnitude is

a count of the number of first order channels throughout the entire system (Shreve 1967, 1974).

Strahler Order and Shreve Magnitude data were extracted using macros written in Arc/Info's Arc Macro Language (ESRI 2000). The output from this code is two attributes assigned to each channel centerline segment: a Strahler Order value and a Shreve Magnitude. The Strahler order values are then used to generate maps showing all channels classified according to order which provide insight into the channel network structure at the study site. The Shreve data for each levee breach are included on those same maps and provide insight into the temporal dynamics of the channel network as well as its overall complexity.

Channel Density

I have calculated two measures of channel density: (1) area/area (in units of percent) in which the surface area of the channel network is divided into the surface area of the intertidal portion of the site (excluding levees), and (2) length/area (in units of ft/ft² or m/m²) in which the total centerline length is divided into the site intertidal area (Strahler 1964). Linear density is more commonly computed in fluvial geomorphology, as it conveys the total stream length within a watershed (Kirkby 1993) and typically available data do not allow for calculation of channel surface area (e.g., streamline data on USGS quad sheets).

Bifurcation Ratio

Bifurcation ratio (R_b) measures the number of tributary splits in a channel. This measure is commonly used in wetland restoration channel design to determine the extent to which the channel network should be branched. It is computed as:

$$R_b = \frac{N_u}{N_{u+1}}$$

where N_u is the number of channel segments of order u and N_{u+1} is the number of channel segments of the next higher order (Strahler 1964). Data presented in this research includes separate calculations for the full channel network (primary and secondary channels) and for the primary channel-only network.

Length Ratio

Length ratio (R_l) measures the relative length of tributary channels to trunk channels. This measure is sometimes used in wetland restoration channel design to determine what lengths to construct various segments of the channel network. It is computed as:

$$R_l = \frac{L_u}{L_{u+1}}$$

where L_u is the length of channel segments of order u and L_{u+1} is the length of channel segments of the next higher order (Strahler 1964). Data presented in this research includes separate calculations for the full channel network (primary and secondary channels) and for the primary channel-only network.

4.3.8 Final Digital Elevation Model

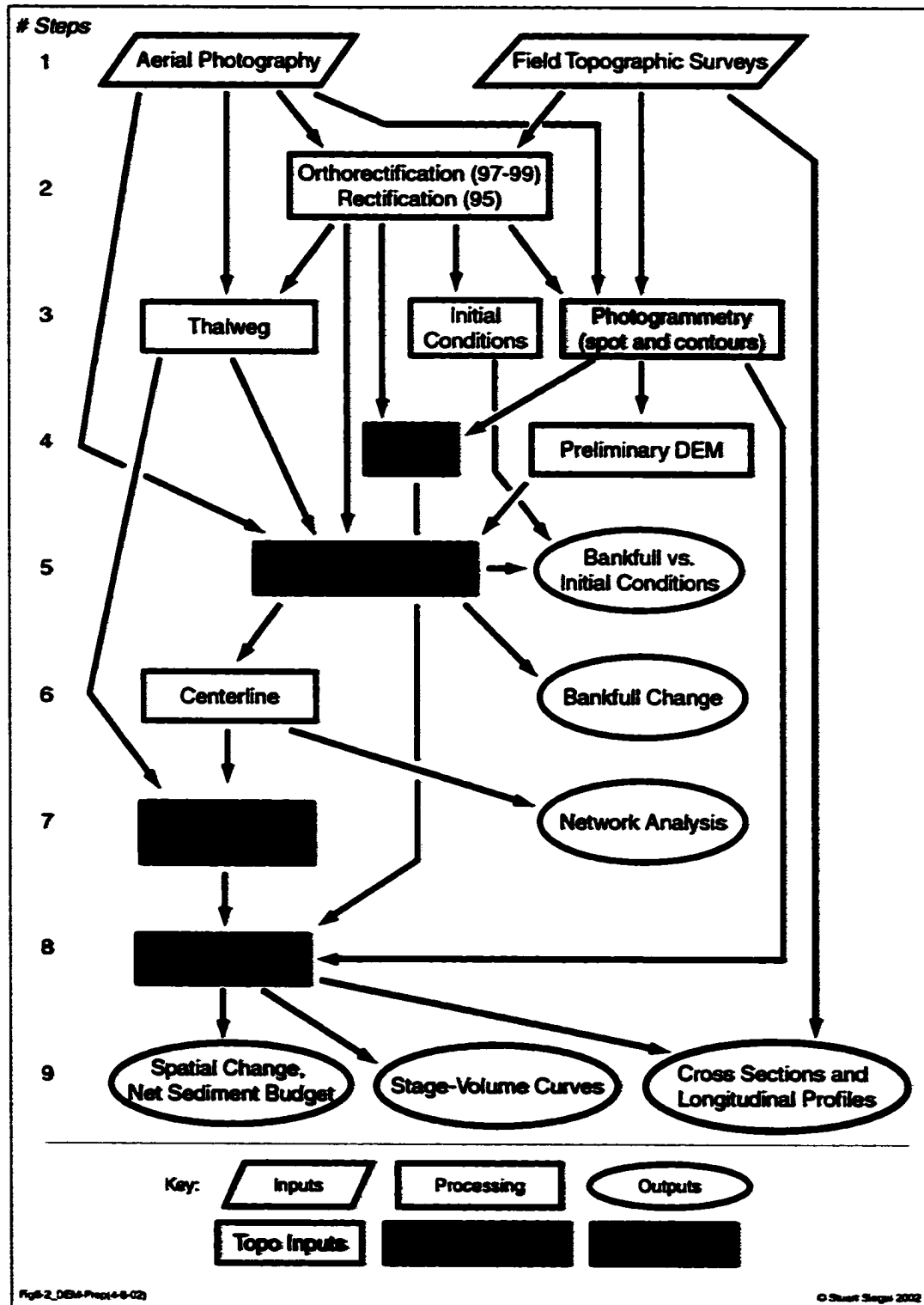
The final digital elevation model (DEM) grids generated for quantitative analysis used several pieces of data developed from the analyses described in the previous sections. These final grids were then error-checked against field data to evaluate their representativeness. Figure 4-3 highlights the data used and the linkages between these data.

Input Data

I used the following input data for the final DEMs:

- Spot elevation data (Map 4-4)
- Channel bankfull as soft breakline (Map 4-5)

Figure 4-3. Data Linkages for Final Digital Elevation Model Generation



- **Hybrid thalweg-centerline coverage as “stream” soft breakline (Map 4-7).**
This coverage provided a complete “flow path” streamline for the entire channel network. It combined the entire thalweg coverage with that portion of the centerline coverage where no thalweg existed.

Final DEM Grid Algorithms

I experimented with several grid generation techniques to arrive at the optimal quantitative integrity (as evaluated through the error checking technique described below) and visual integrity (as evaluated via a visual examination of the resultant grid). The method that yielded the best results consisted of the following steps:

- **TIN (triangulation), based on the Delauney algorithm (Wolf and DeWitt 2000) using spot elevation data, bankfull breaklines, and hybrid thalweg-centerline breaklines**
- **Export point data from TIN to use in ArcInfo® TOPOGRID routine**
- **TOPOGRID using TIN-exported point data, bankfull breaklines, and hybrid thalweg-centerline breaklines**

Each of these steps has multiple settings for adjusting the output. After trying several dozen options, I could not determine any single set of parameters to provide the “optimal” grid output. Consequently, I opted to select the five best sets of parameters

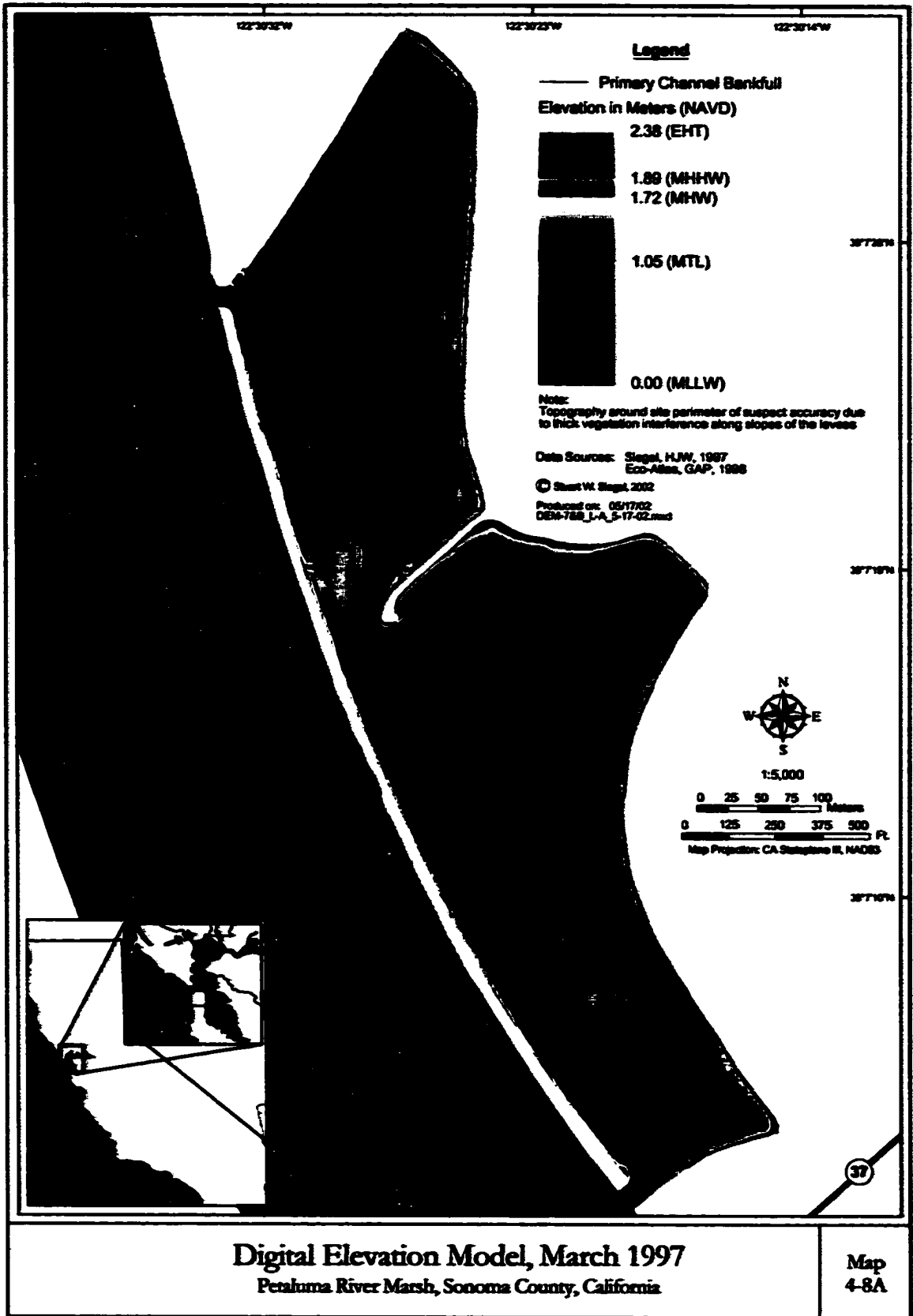
and generate five grids for each year, average the numerical results for the cross sections and long profiles (Section 4.3.9) and the net sediment accumulation (Section 4.3.10), and show the results for one set of parameters as Map 4-8.

DEM Error Checking

Examining the vertical accuracy of the resultant DEMs is an important step in understanding the limitations in applying these data. Standard protocols recommend at least 20 map points be used to calculate RMSE (root-mean-square error) values (Wolf and DeWitt 2000). Here I used approximately 40 map points.

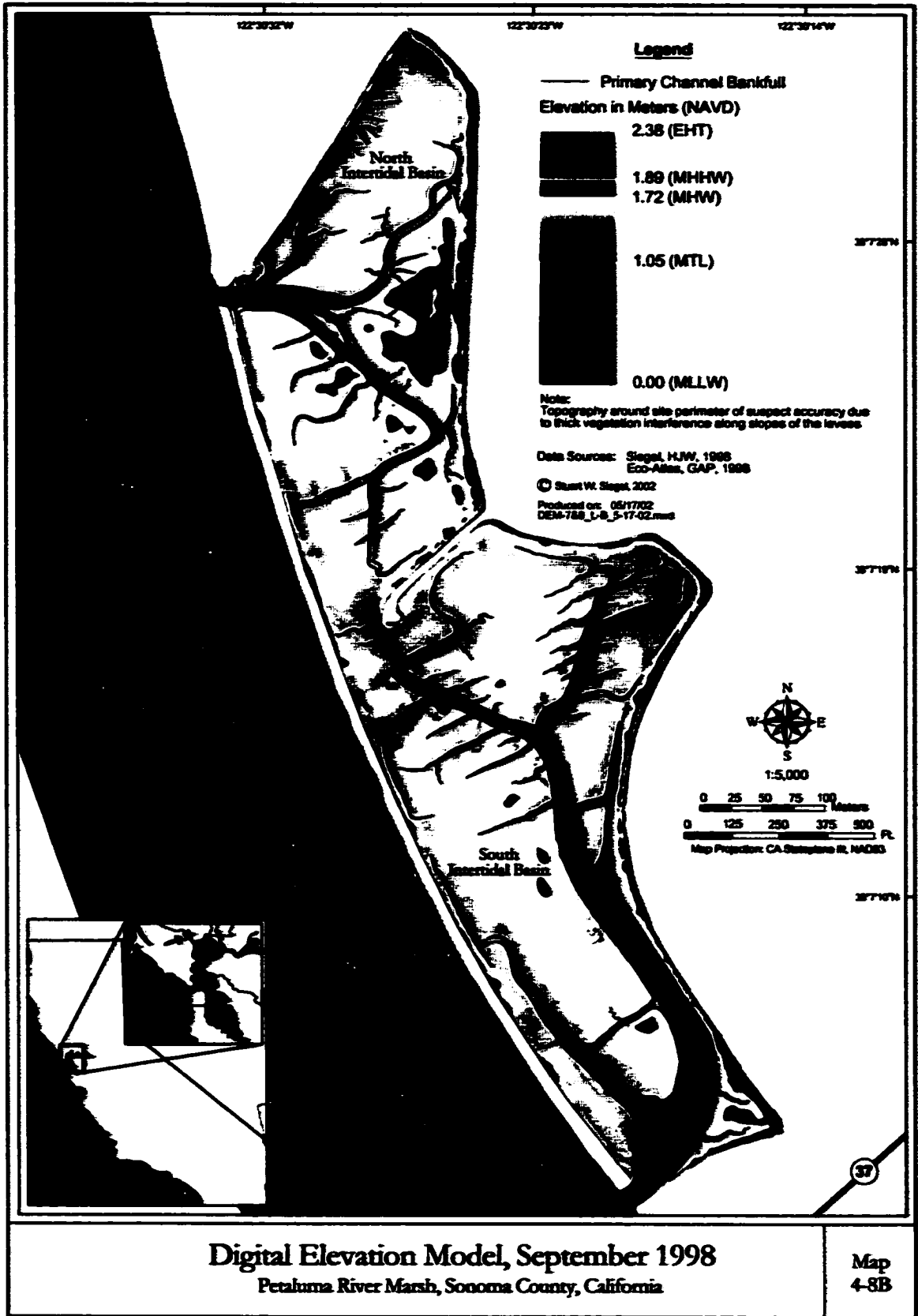
4.3.9 Channel Cross Sections and Long Profiles from DEM Data

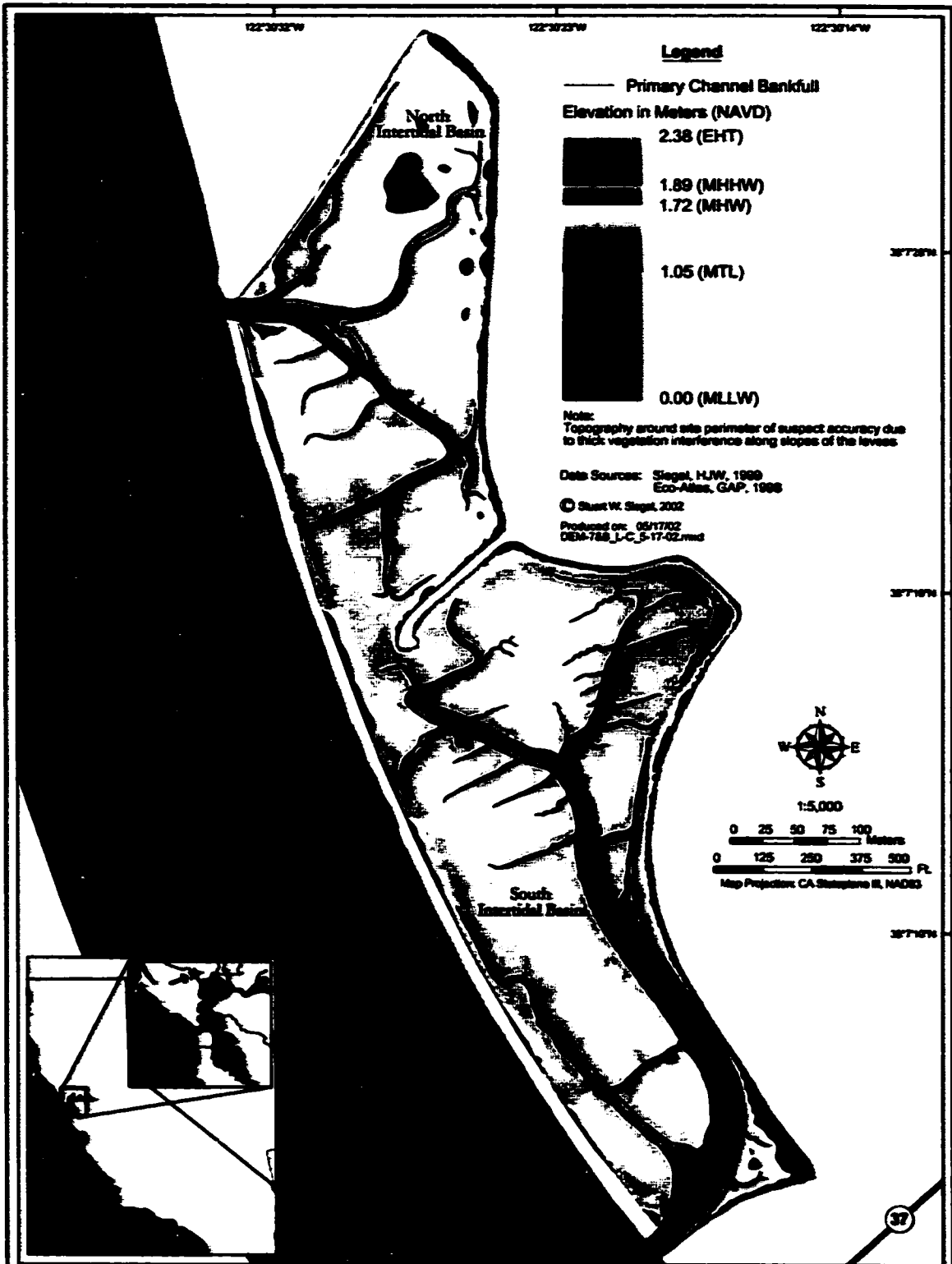
The GIS coverages generated through the many preceding steps provide the data necessary for quantifying channel cross section and longitudinal profile morphology. From the DEM grids I extracted elevation data along selected arcs representing channel cross sections (four corresponding to field data) and long profiles. For each arc I obtained the horizontal distances referenced to a selected zero end point and the elevation for each grid element crossed by the selected arc. I then used these data in standard two-dimensional software to plot cross sections and long profiles.



Digital Elevation Model, March 1997
Petaluma River Marsh, Sonoma County, California

Map
4-8A





Digital Elevation Model, August 1999
Petaluma River Marsh, Sonoma County, California

Map
4-8C

4.3.10 Net Sediment Accretion from DEM Data

I have calculated net sediment accretion for the entire site from the topographic differences between the successive DEMs by overlaying successive DEMs and calculating height difference for each pixel. I performed three comparisons: 1997 to 1998, 1998 to 1999, and 1997 to 1999. The net sediment volumetric accretion represents the actual change in surface elevation between these time periods for each pixel multiplied by the surface area of that pixel. Net accretion therefore integrates all the physical and biological processes acting to increase and decrease site elevations. I then estimated sediment mass for each DEM interval by utilizing bulk density data derived from 1997 sediment cores (Section 4.2.4) to represent early conditions or from literature values of more consolidated tidal marsh sediments to represent later conditions. Without actual field measurements, these estimates introduce some uncertainty into the calculated sediment mass values.

4.4 Calculating Net Sediment Flux

Net sediment flux per tide, in units of mass, is calculated as:

$$\text{Net Sediment Flux} = \text{Sediment Input} - \text{Sediment Output}$$

Values are greater than zero indicate net sediment influx per tide, and values below zero indicate net sediment output (erosion) per tide.

Sediment inputs and outputs are calculated as the incremental change in water volume between two tide level and SSC measurements multiplied by the SSC value for that increment, summed over the flood tide (inputs) and ebb tide (outputs).

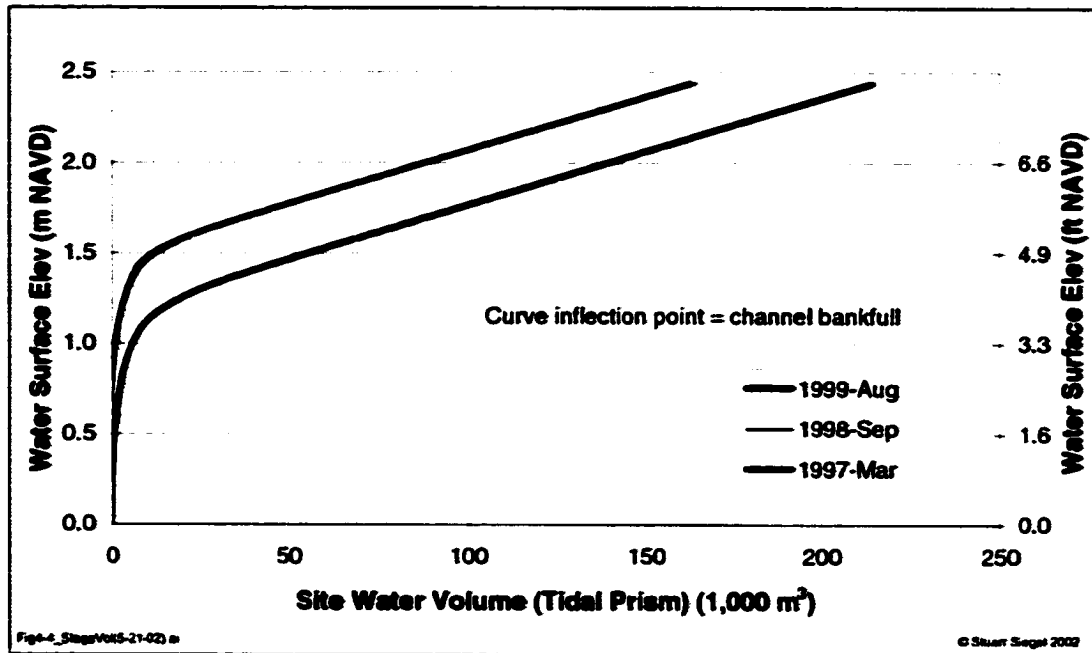
$$\text{Input} = \sum (\text{water volume}_{i, \text{ flood tide}} \cdot \text{SSC}_{i, \text{ flood tide}})$$

$$\text{Output} = \sum (\text{water volume}_{i, \text{ ebb tide}} \cdot \text{SSC}_{i, \text{ ebb tide}})$$

where i = slack low water to slack high water (flood tide) and slack high water to slack low water (ebb tide), at 12-minute increments following water level and SSC measurement frequencies. Since the site drains completely on most tides, only those time increments where water is present and measured by the field instruments are used in this calculation.

Volume data come from volume hypsographs (stage-volume curves) generated from each of the DEMs, shown in Figure 4-4, with interpolation between DEMs to provide the volume data for each time step.

Figure 4-4. Stage-Volume Hypsometric Curves from DEMs



All data used in these calculations are from the SC station (see location in Map 4-1). This station is close to the South Breach and thus is used as representative of the flux into and out of that breach with the assumption that fluxes through the North Breach are of equal concentration to the South Breach based on similar physical processes affecting sediment concentrations. This assumption may not be valid at all times and thus the flux calculations contain a somewhat greater level of uncertainty at an absolute scale though probably retain lesser uncertainty on a relative scale. Further, these calculations also assume a vertically mixed water column with no significant SSC gradients. In practice, that assumption is likely to be valid on windier days when the water column would be well mixed and may not be as valid on calm days when the water column would be poorly mixed (Christie *et al.* 1999).

Chapter 5.0 Temporal and Spatial Accretion Patterns

Net sediment accretion informs restoration design by describing the temporal and spatial accretion patterns and their relationship to sediment load, initial geomorphic conditions at the site, and external physical, chemical, and biological processes interacting with the evolving ground surface at the site. Net sediment accretion measures the sedimentation from an ecological perspective – what is the elevation of the site with respect to the tides which defines the dominant physical controlling mechanism on tidal marsh ecology. Specific questions regarding net sedimentation include:

- *How do patterns of accretion differ between the marsh plain and channels?*
- *How do patterns of accretion vary as a function of starting elevation?*
- *How do patterns of accretion vary spatially around the site?*

To address these questions in the context of applying the results as tidal marsh restoration design tools, I have collected and analyzed a variety of data. Digital elevation models (DEMs) provide an absolute difference in elevation over time. Limited bulk density can be used to convert volumetric results from DEM analysis into mass values. Time series water column monitoring of water level and suspended

sediment concentration (SSC) can be combined with volume hypsographs derived from the DEMs to evaluate overall sediment flux in a volumetric and mass approach.

This chapter is organized into the following sections:

- **Mass flux measurements (Section 5.1)**
- **DEM elevation changes (Section 5.2)**
- **DEM volume and mass net accretion (Section 5.3)**
- **Sediment pins (Section 5.4)**
- **Sediment grain size (Section 5.5)**
- **The prograding delta model (Section 5.6)**
- **Feedback mechanisms affecting elevation (Section 5.7)**
- **The 1997-1998 El Niño Event**

I have quantified the net sediment accretion in two ways in an attempt to provide the best estimate and understand the physical processes that may influence accretion. The first approach (Section 5.3) draws from differences between DEMs for each year (which provides a relatively accurate output) combined with limited bulk density data to convert volumetric results into mass values (which yields some measure of uncertainty in the mass values). This approach yields results that are “net” in that it represents the combined action of every process – physical, chemical, and biological – that has acted on the site to raise or lower ground surface elevations. Sediment

deposition is the primary process that raises elevations, and erosion, compaction, consolidation, and reworking by biota can all contribute to a lowering of the elevation.

The second method calculates a per-tide net sediment flux value, quantifying sediment mass imported or exported over each tidal cycle. The cumulative net sediment influx provides an estimate of sediment mass that deposited during the period monitored and can be compared to the DEM- and bulk density-derived mass estimate. Each method of calculating sediment accretion provides a check on the other methods. To the extent that each method generates directly comparable numeric values, then some estimate might be made of the “actual” accretion in contrast to the particular uncertainties of any one method.

5.1 Suspended Sediment Mass Flux Measurements

The purposes of calculating net sediment flux measurements per tide are (1) to examine temporal patterns of change in sediment flux, (2) identify temporal patterns of peak sediment flux as part of an effort to understand what events appear to constitute dominant geomorphic tides, (3) to cross-check DEM- and bulk density-derived sediment accretion results. This section addresses the third purpose in particular, for comparison with the DEM results presented in Section 5.3.

This section presents the results of calculating net sediment flux per tide from the time series water level and suspended sediment concentration data combined with volume hypsographs derived from the DEMs. This approach yields results as sediment mass and, because of assumptions necessary to perform the calculations, carries some measure of uncertainty in the absolute numerical results yet provides a very meaningful temporal comparison. A “tide” is defined here as the rise and fall of the tides beginning and ending with two successive low tide events.

5.1.1 Assumptions Used and Potential Effects on Results

The sediment flux measurements are based on SSC values from the SC station, which is located close to the South Breach with the sensor mounted relatively close to the channel bed in order to maximize period of valid (inundated) measurements in an intertidal environment. I have made a number of assumptions in order to perform flux measurements based on these data.

Assumption 1: SSC values from the SC station are representative of concentrations entering the site via the South Breach. Since the measurement station is relatively close to the South Breach and within the channel, this assumption should be reasonably valid.

Assumption 2: SSC values from the near-bed sensor measurement position are representative of sediment concentrations throughout the water column that enters the site. In other words, I am assuming no vertical gradients in sediment concentration at any time. This assumption is essentially valid under many conditions but there exist distinct conditions where it is not. However, it is a critical simplifying assumption for the purposes of this calculation. Further calculations would provide a better quantification of flux values.

When the water column is well mixed, there will exist little if any vertical gradient (e.g., Mitchener and O'Brien 2001) and this assumption will hold. Such conditions occur routinely during windy periods as well as during large spring tides.

This study included about 465 of 1,086 tides (43%) in which water column vertical gradients were measured. Appendix B includes the full time series data set in graphic format. Three general regimes emerge regarding vertical SSC structure from that data:

- **SSC regime 1, minimal to very small vertical gradients,** is the most common occurrence through each tide. Vertical drops in SSC often range from roughly 0-5% with a few data points reaching perhaps 10%. Under this regime, this assumption is likely to introduce only small uncertainty at most.

- **SSC regime 2, large vertical gradients at high tide, occurred on about 60 of the 465 tides (13%) with vertical gradient SSC measurements.**

Divergences in many cases were 200-300% and occurred for extended periods around high water. High water corresponds with large water volume (tidal prism) filling the site and translates into the maximum overestimate of each component of the flux – flood tide imports and ebb tide exports. Since I am calculating net flux (import minus export), these overestimates may balance out, leaving a comparatively small uncertainty in net flux. Whether they balance is determined in large part by the extent to which the gradient occurs during both flood and ebb tides. A qualitative examination of the time series data presented in Appendix A shows that, in some circumstances, there is observable weighting into the ebb tide and in some instances into the flood tide. Ebb weighting overestimates export and thus underestimates net influx, whereas flood weighting reverses those patterns. The overall affect this regime exerts on uncertainty about the net influx values is difficult to assess and warrants further exploration.

- **SSC regime 3, medium vertical gradient during flood tides, occurs infrequently (Appendix B). It would overestimate flood tide influx and consequently overestimate net influx.**

The current calculations do not take into account periods when vertical gradients exist, so each flood and ebb flux value would likely be an overestimate. Consequently, these

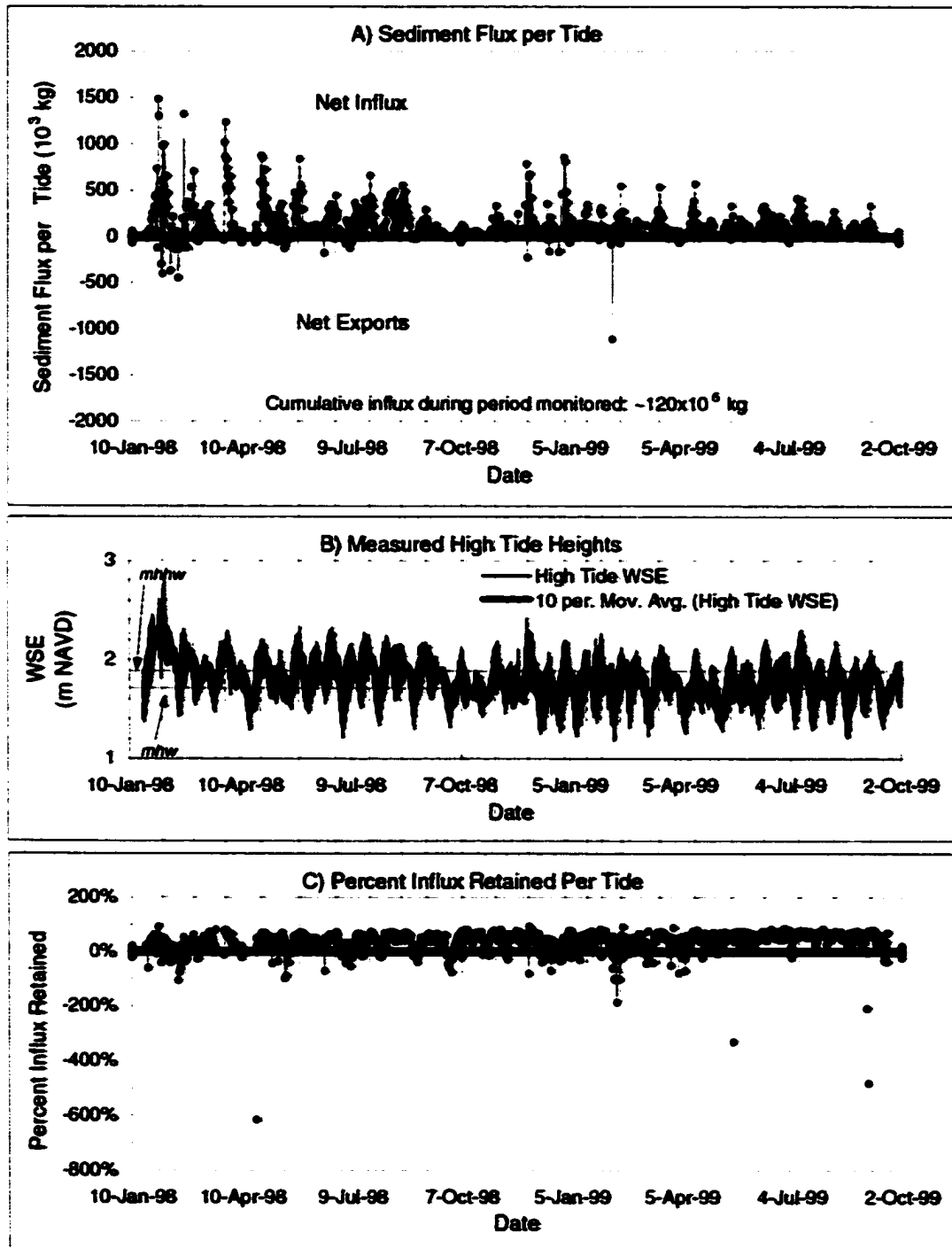
flux measurements may not yield absolute quantitative results but are likely within a 10-20% range of the actual values. However, because the important indicator here is *net* flux, then all that matters is whether the absolute difference remained constant or changed. Further work would be necessary to assess that difference.

Assumption 3: SSC values from the SC station are representative of concentrations entering the site via the North Breach. Since both levee breaches receive water inputs from the same large Petaluma River source and since there are no geomorphic shifts in this reach of the river that may alter sediment supply, incoming concentrations are likely to be fairly similar between the two breaches. Consequently, this assumption is likely to be valid under most conditions.

5.1.2 Sediment Flux Results

A total of 1,086 tides from 20 January 1998 to 20 September 1999 have combined water level and suspended sediment concentration data valid for calculating sediment flux. Section 4.4 presents the analytical methods employed. Figure 5-1 shows these flux results, with panel (A) showing the net flux per tide and panel (B) showing the percent of influx retained with each tide. The purpose of panel (B) is a data quality measure that evaluates the signal strength; large percent retained (or lost) suggests a strong flux signal whereas small (e.g., <10%) suggests a potentially weak flux signal.

Figure 5-1. Sediment Flux and Tide Height, from Time Series Data



To identify possible correlative relationships, the vertical dashed lines align the peak net sediment influx events with the associated high tide and percent influx retained plots. The suggested correlation is net influx is dependent on higher spring tides of each month.

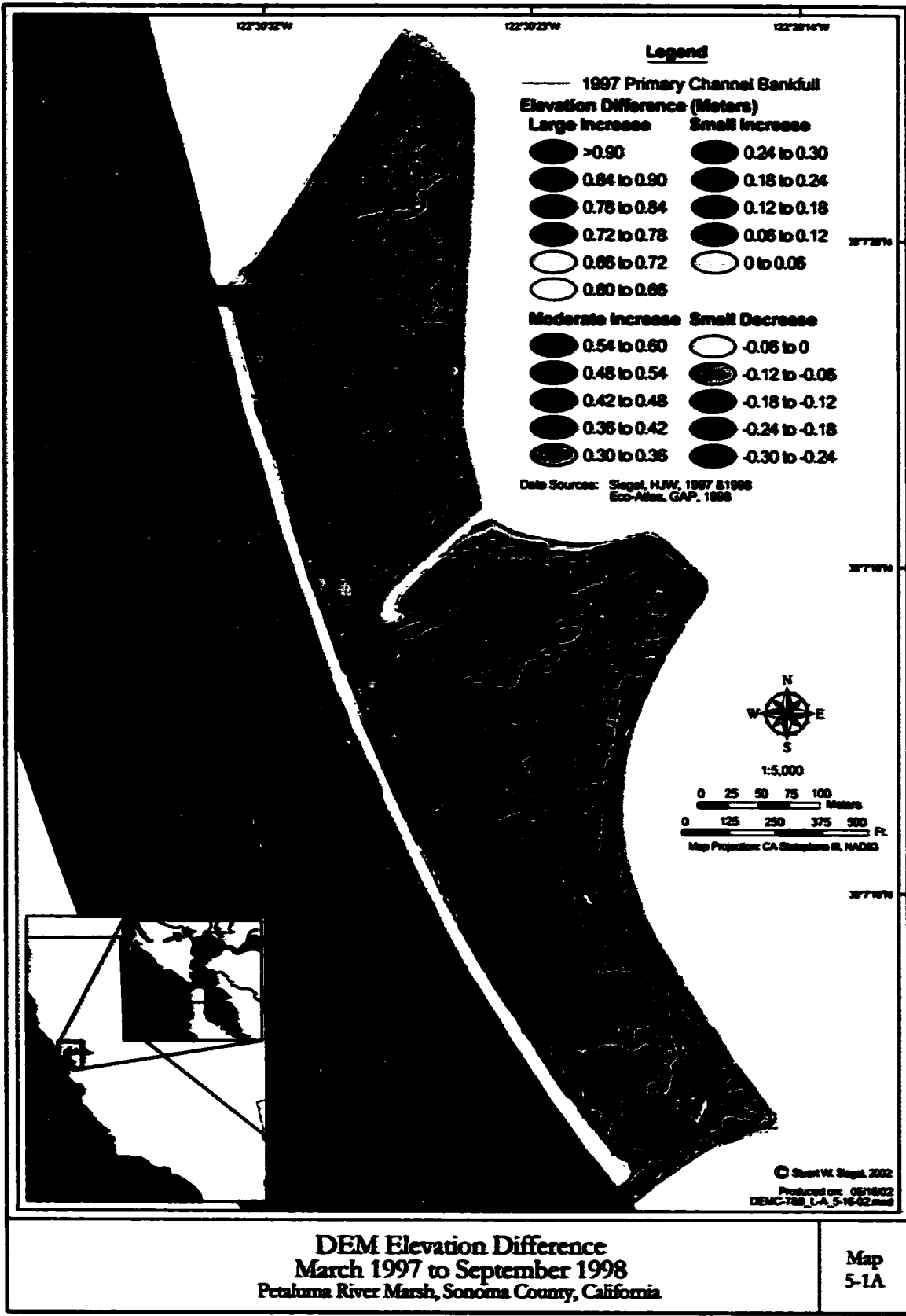
These data enable of number of insights regarding sediment flux into the site during the study period. First, under most conditions, a net accretion occurs with each tidal cycle. Of the 1,086 tides used in these calculations, 129 tides (11.8%) resulted in sediment export from the site. Second, the median percent influx retained is 48% and only 8 tides (0.7%) exported more sediment during the ebb tide than entered during the flood portion of the measured tide (i.e., resulted in net scour). In other words, throughout the entire study period, sediment accretion occurred. Third, there is an overall decline in peak net influx during the study period, a phenomenon likely related to a smaller tidal prism at the site as elevations increased and perhaps as overall high tide heights declined over time. Fourth, there is a distinct temporal pattern of peak net influx events coincident with the higher of the two monthly spring tide events. Finally, the cumulative sediment influx during the study period is approximately 120 million kilograms of sediment, a value which will be contrasted in Section 5.3 to the results obtained from the DEM analyses.

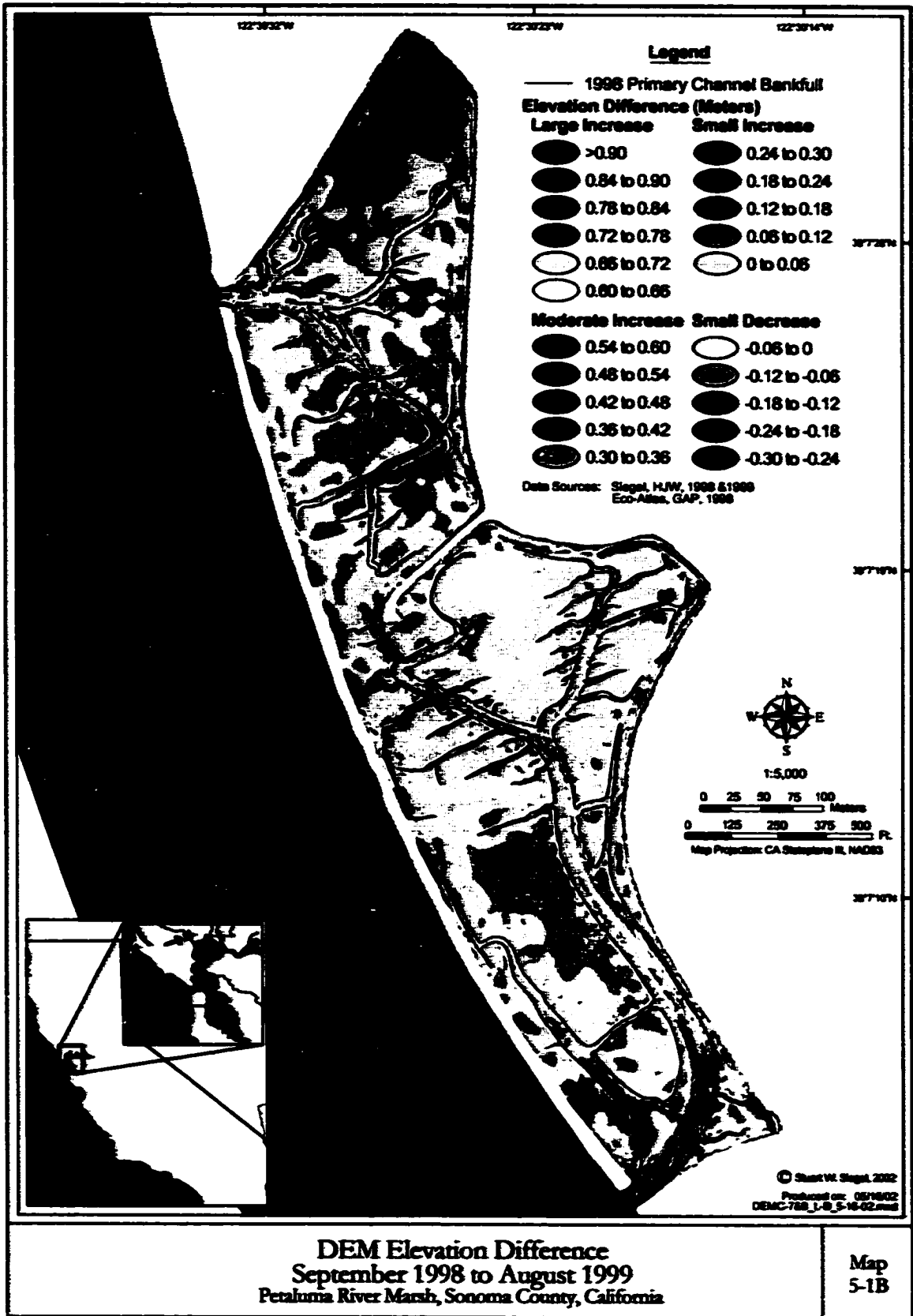
5.2 Marsh Plain and Channel Elevation Changes

Map 5-1 shows the topographic change between the DEMs. Map 5-1A shows change from March 1997 to September 1998 (1.5yr duration), Map 5-1B shows the period from September 1998 to August 1999 (1.0yr duration), and Map 5-1C covers the entire period of March 1997 to August 1999 (2.5yr duration). Uncertainty in topographic change for these data is $\pm 0.07\text{m}$.

The most striking results shown in Map 5-1 are the temporal patterns of changes in ground surface elevation. Overall, site elevations increased by up to 0.6m over the period measured (Map 5-1C). However, most of this increase occurred from March 1997 (year 2.6) to September 1998 (year 4.1). The latest period, September 1998 to August 1999 (year 5.0), showed a divergent pattern (Map 5-1B): much of the site had either small elevation decreases (about 0.1m) or modest increases (again, about 0.1m). Much of these data fall close to or within the uncertainty level of $\pm 0.06\text{m}$. In other words, the period monitored captured the transition from a rapidly accreting environment to a slowly accreting environments.

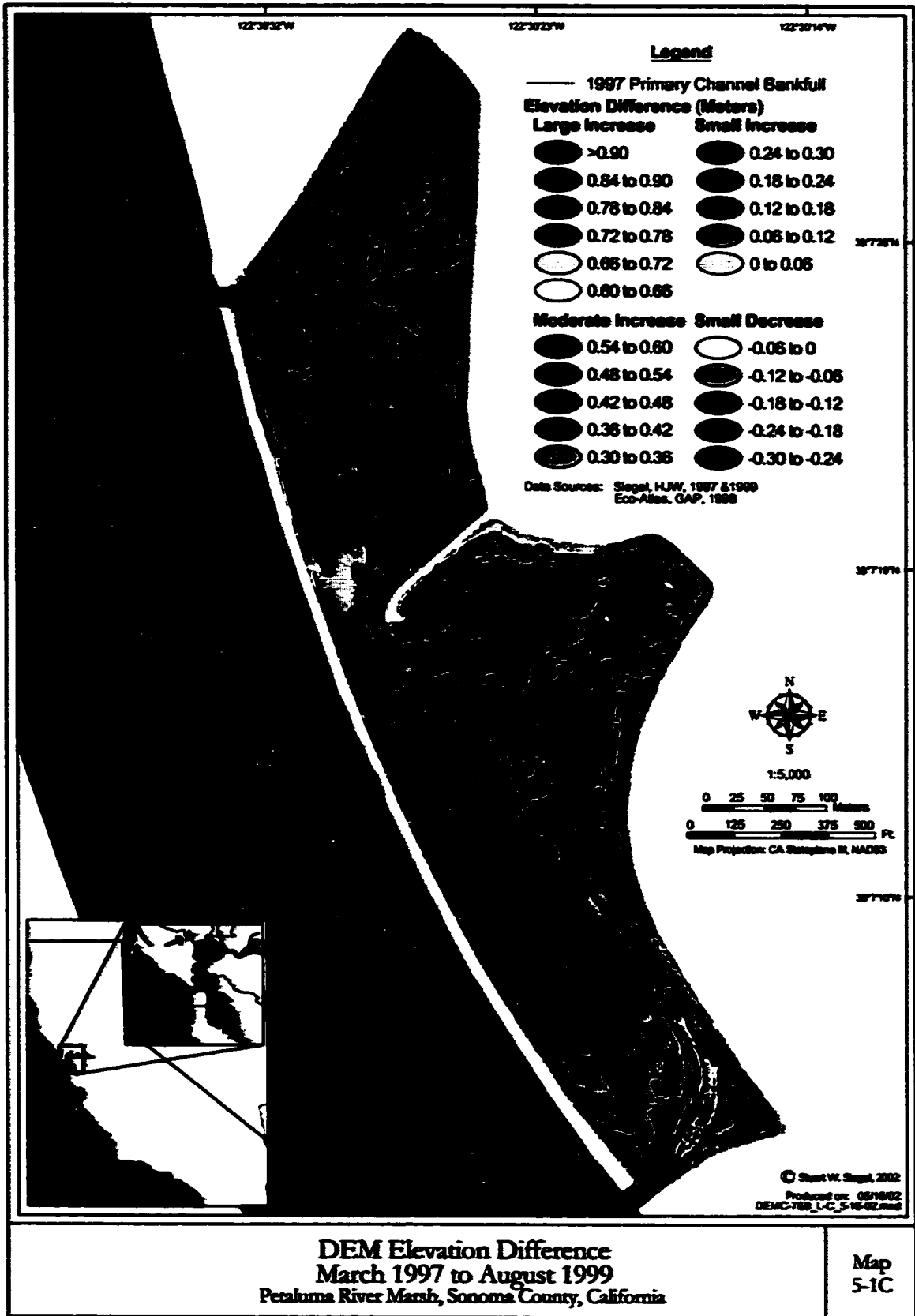
Elevation increases in the channels exhibited a wide range of variability. The greatest elevation increases anywhere on site occurred within the large South Channel a short distance inside the South Breach (where increases reached nearly 1m) and in a smaller channel in the North Basin. Channel bankfull boundaries are included on Map 5-1 to highlight the spatial relationship between amounts of net sedimentation and channels. In most areas of large channels, there was a greater amount of net sedimentation relative to adjacent mudflat/marsh plain, meaning the channels were becoming progressively shallower over time. Sections 6.2 (cross sections) and 6.3 (long profiles) in Chapter 6 provide data that demonstrate this result further, as does additional data shown in Figure 5-2 below.





DEM Elevation Difference
September 1998 to August 1999
 Petaluma River Marsh, Sonoma County, California

Map
5-1B



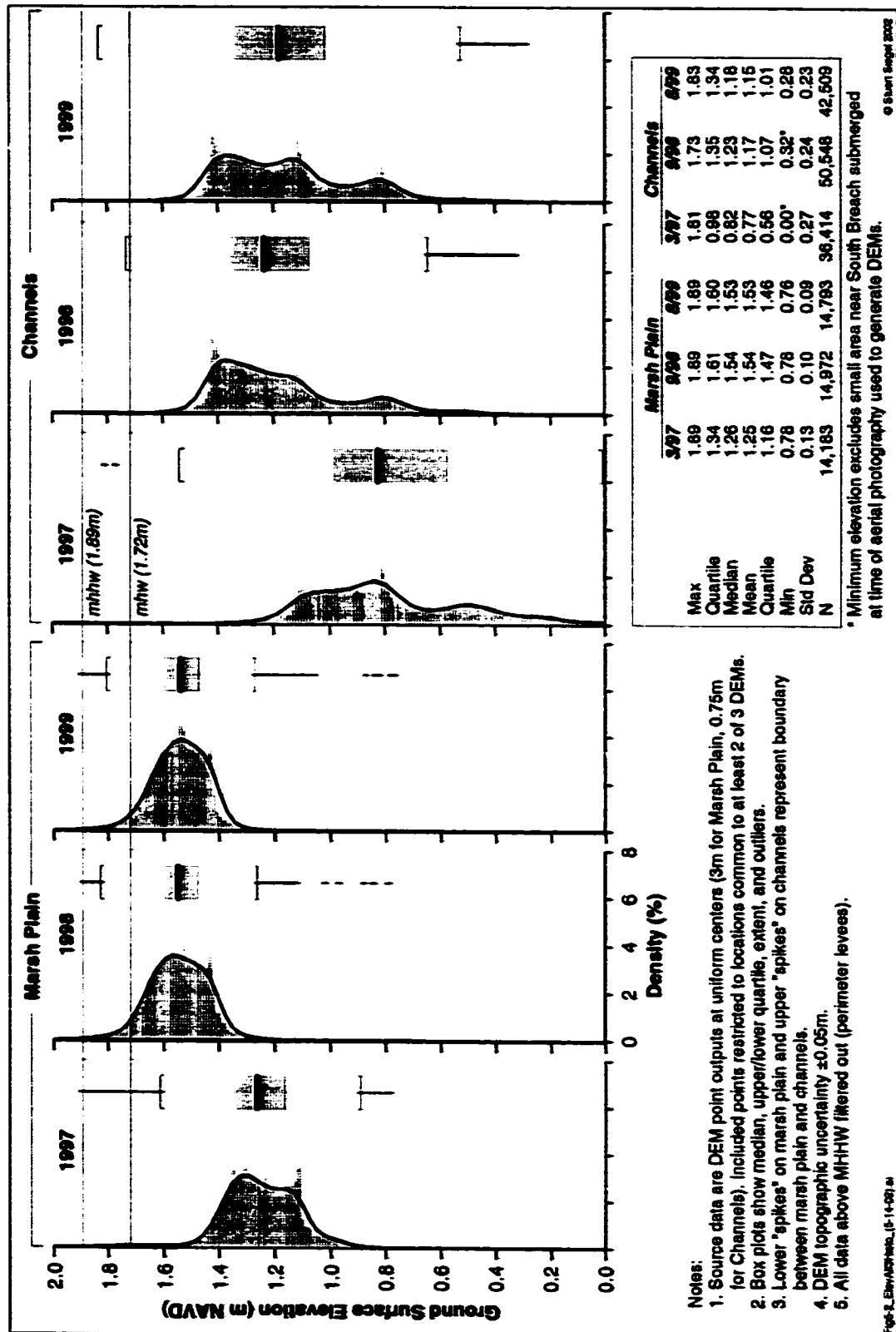
5.2.1 DEM Topography

The DEM graphic data presented in Map 4-8 (Chapter 4) and in Map 5-1 can also be evaluated numerically. For those evaluation, I have extracted spot elevation data separately for the marsh plain and channels, using a regular grid of points at 3m (10ft) and 0.75m (2.5ft) spacing, respectively. Figure 5-2 presents the histogram of the spot elevations for each DEM (Map 4-8), and Figure 5-3 presents the histogram of the accretion rates for each DEM change (Map 5-1). Figure 5-4 then plots the rates from Figure 5-3 against the elevations from Figure 5-2 and includes results from a linear model fit of this relationship.

The elevation histogram data in Figure 5-2 reveals a number of attributes of topography for each DEM. Note that each histogram is plotted with matching vertical and horizontal scales.

- 1. Marsh plain topographic change.** Marsh plain median elevations in March 1997, September 1998, and August 1999 were 1.25m, 1.54m, and 1.53m, respectively. Clearly, 1998 and 1999 elevations were virtually identical and distinct from the 1997 elevations, which were lower by about 0.3m. These data reflect the rise in the marsh plain with ongoing sediment accretion over time and the change from continuing elevation increases to no elevation increases.

Figure 5-2. Topography Distributions from DEMs, Marsh Plain and Channels



2. **Marsh plain topographic ranges.** The ranges of marsh plain elevations in 1998 and 1999 were fairly similar, with 1999 having a slightly narrower range (note box plots within Figure 5-2) and both 1998 and 1999 having a slightly narrower range than 1997. These results suggest an increasing topographic “definition” or expression of the marsh plain with time.

3. **Marsh plain elevations in relation to tidal datums.** In 1997, the median marsh plain elevation was 0.46m below local MHW. In 1998 and 1999, the marsh plain elevations were 0.18m and 0.19m below local MHW, respectively. The essentially unchanged marsh plain topography from September 1998 to August 1999 suggests that the site had reached an elevation at which the multiple forces acting to increase elevations (ongoing sediment accretion) and decrease elevations (consolidation, compaction erosion) were balancing out. We know from Section 5.1 that during this period, there existed a continued net sediment influx into the site. These results together suggest there may exist an elevation threshold (about 0.2m below local MHW at this site) at which continued elevation increases in absence of vegetation colonization does not occur.

4. **Channel topographic change.** Channel median elevations in March 1997, September 1998, and August 1999 were 0.77m, 1.17m, and 1.15m, respectively. These data reflect a dynamic channel network the elevations of which rise upward concurrent with adjacent marsh plain. Interestingly,

channels elevations increased more rapidly during the period monitored compared to the marsh plain, having risen about 0.4m versus 0.3m for the marsh plain. These data indicate an overall decreasing volume of the channels with time as the marsh accretes (i.e., channel shallowing).

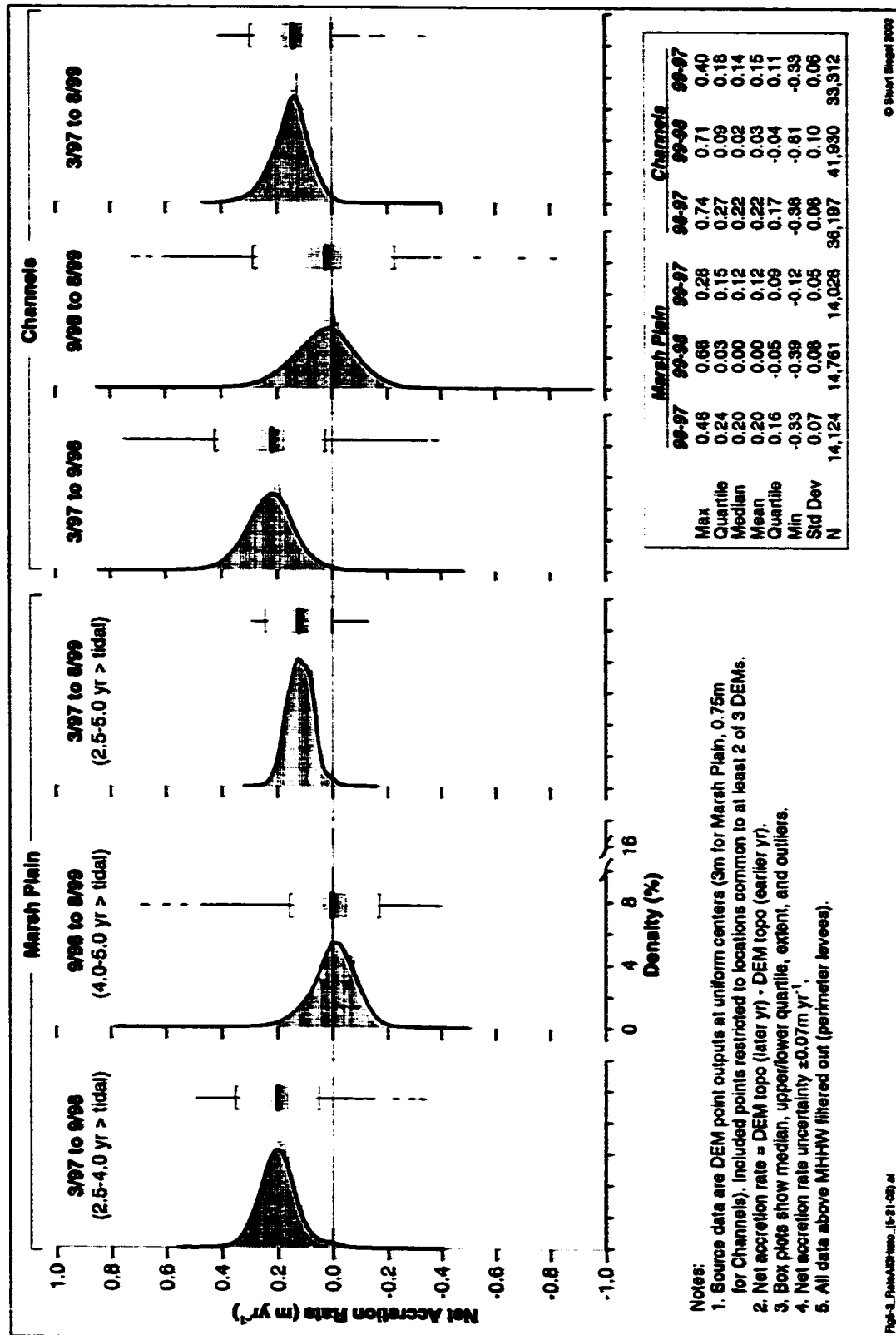
5. **Channel topographic ranges.** The ranges of channel elevations are quite large and are of differing magnitudes between years. These results indicate a broader range of topographic conditions for site channels compared with the marsh plain, which one would expect for a channel network comprising channels of widely varying size.
6. **Marsh plain – channel corresponding peaks.** There is a corresponding elevation peak at the lower end of the marsh plain and the upper end of the channel elevation data that corresponds to the transition between marsh plain and channel. These peaks signify the quantity channel edge interface with the adjacent marsh plain, with more interface desired ecologically.
7. **Channel tri-modal elevations.** Each channel elevation histogram shows a tri-modal distribution with nearly equal vertical spacing that is maintained while channels rise vertically over time. Following the marsh plain/channel interface analogy in the previous item, these modes may represent transitions between groups of channels of relatively similar geometry and thus there may exist three distinct channel geometry's at the site.

5.2.2 DEM Net Accretion Rates

The accretion rate histogram data in Figure 5-3 reveals a number of attributes of sediment accretion between each DEM. Note that each histogram is plotted with matching vertical and horizontal scales.

- 1. Marsh plain cumulative net accretion rates decrease with time.** The cumulative net accretion rates dropped from median values of 0.20m yr^{-1} for March 1997 to September 1998 to 0.12m yr^{-1} for March 1997 to August 1999. These results are what one would expect, as the period of inundation (and hence accretion potential) decreases with increasing elevations. These data are lower than the sediment pin-derived data presented in Section 5.5. One reason for this difference may be that data presented in Figure 5-3 are from over 14,000 points from the DEM grid representing nearly all configurations of the marsh plain, whereas there were five sediment pins installed originally and another 14 added later on, clearly a small number to characterize the full range of marsh plain accretion conditions.

Figure 5-3. Net Accretion Rate Distributions from DEMs, Marsh Plain and Channels



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Fig-5_PlanAccrRate_05-21-02.m

2. **Marsh plain interval net accretion rate for 1998 to 1999 is zero.** The period from September 1998 to August 1999 showed a median net accretion rate of $0.00 \pm 0.07 \text{ m yr}^{-1}$. This median and uncertainty range encompass about 70% of the data. Outside these data were a large number of outliers spanning net accretion rates as high as 0.68 m yr^{-1} and as low as -0.39 m yr^{-1} . These data indicate the variable conditions of net elevation change in the 1998 to 1999 monitoring interval.

3. **Marsh plain net accretion rate range variability.** The range of marsh plain net accretion rates shown in Figure 5-3 is the greatest for 1998-1999, intermediate for 1997-1998, and the least for 1997-1999. These results suggest an evening out of the ground surface over time, a topic discussed further in Section 5.6.

4. **Channel cumulative net accretion rates decrease with time.** The cumulative net accretion rates dropped from median values of 0.22 m yr^{-1} for March 1997 to September 1998 to 0.14 m yr^{-1} for March 1997 to August 1999. These results are what one would expect, as the period of inundation (and hence accretion potential) decreases with increasing elevations.

5. **Channel interval net accretion rate for 1998 to 1999 is nearly zero.** The period from September 1998 to August 1999 showed a median net accretion rate of $0.02 \pm 0.07 \text{ m yr}^{-1}$. This median and uncertainty range

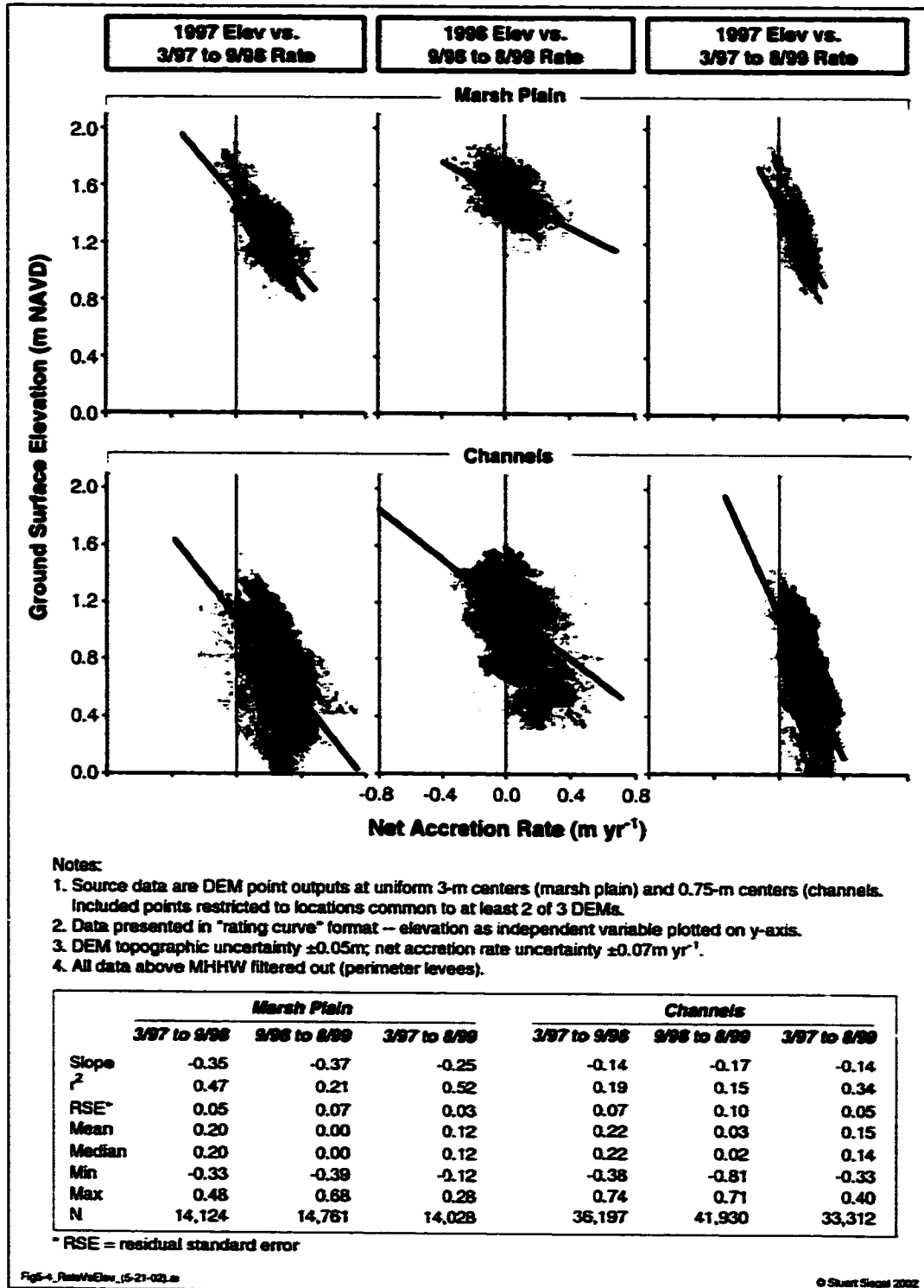
encompass about 50% of the data, less than that for the marsh plain data. Outside these data were a large number of outliers spanning net accretion rates as high as 0.71m yr^{-1} and as low as -0.81m yr^{-1} . These data indicate the variable conditions of net elevation change in the 1998 to 1999 monitoring interval within the topographically diverse channels (see Figure 5-2).

6. **Channel net accretion rate range variability.** The range of channel net accretion rates shown in Figure 5-3 is the greatest for 1998-1999, nearly as great for 1997-1998, and much less for 1997-1999. These results suggest an evening out of the ground surface over time, a topic discussed further in Section 5.6.

5.2.3 DEM Elevation versus Net Accretion

The data in Figure 5-4 describe net accretion rates as a function of starting elevation. I have fitted a least-trimmed-squares linear regression model (MathSoft 1999) to each data set; I evaluated other models to examine for different levels of goodness of fit (e.g., robust linear, exponential, etc.). All models return fairly similar results with comparable residuals, suggesting that no one model is clearly superior to any other. Further analysis of these and other fit models may yield one model that stands out over those already examined.

Figure 5-4. Elevation vs. Net Accretion Rate from DEMs, Marsh Plain and Channels



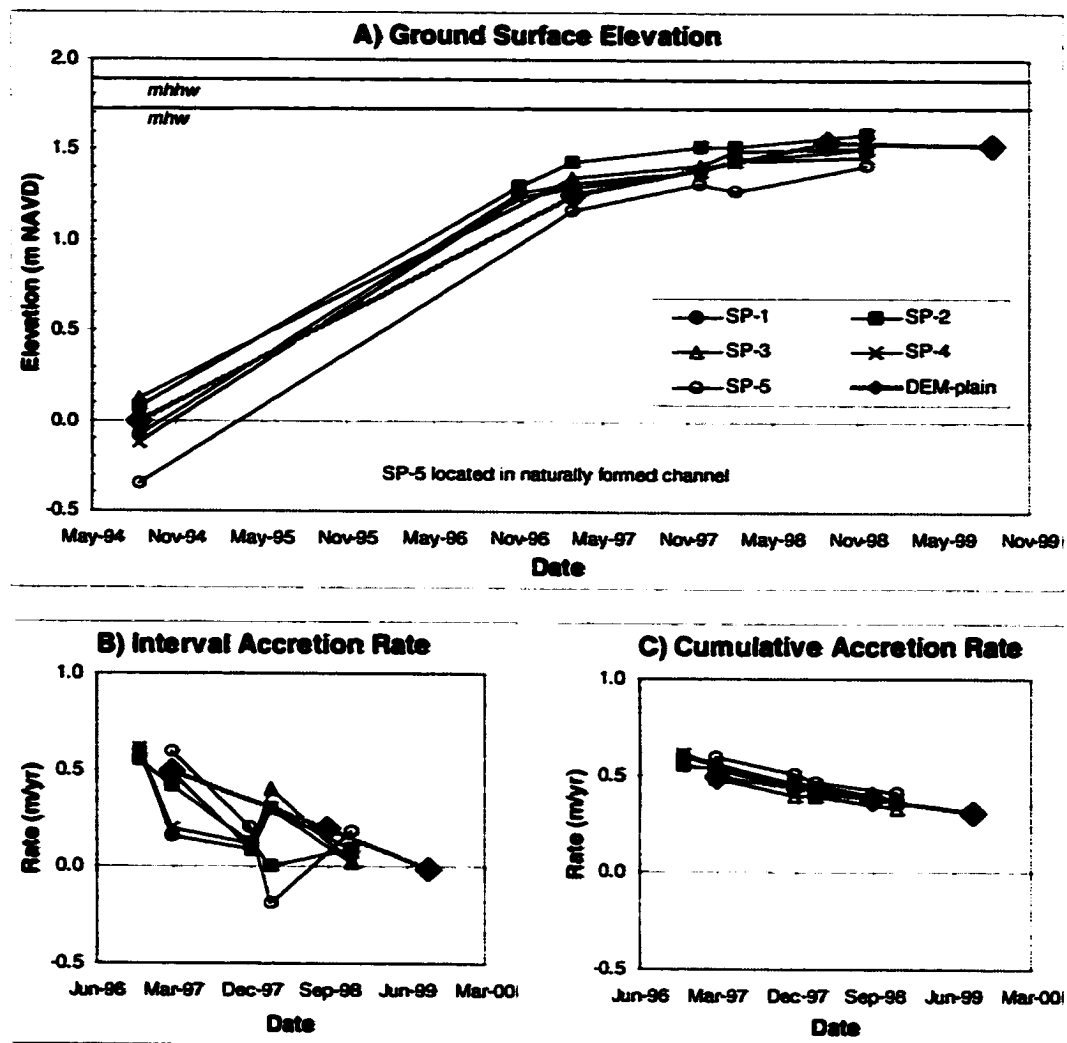
All results show an inverse relationship between elevation and net accretion rate. The strength of this relationship, as measured by the r^2 value for each regression, varies for each data set. The marsh plain data have higher r^2 values relative to the channel data for each comparison period. For example, the 1997-1998 r^2 value for marsh plain is 0.47 versus 0.19 for channels. The 1997-1999 marsh plain r^2 value is slightly better than the 1997-1998 value (0.52 vs. 0.47).

5.3 Sediment Pins

Figure 5-5 shows sedimentation rates as measured from five sedimentation pins installed by the California Department of Fish and Game (CDFG) prior to restoring tidal action. In March 1997 when field work began 2.5 years after restoration, approximately 1.2 m (4.0 ft) had accumulated at the site, corresponding to an annual sedimentation rate of 0.5 m/yr (1.5 ft/yr) (SSWWR 1998).

Midway through the field collection effort, a large magnitude ENSO (El Niño) event occurred, resulting in severe winter storm conditions in early 1998 and elevated sea level for approximately 9 months. Field measurements taken in December 1997 and February 1998, 2.3 months apart, showed sedimentation at the site of about 0.15 m (0.5 ft) (Figure 5-5). This short-term rate would equal 0.75 m/yr (2.5 ft/yr) had it sustained for an entire year.

Figure 5-5. Net Sediment Accretion, Sediment Pins Compared to DEM



This figure shows site topography and rates of topographic change (accretion rates) derived from five sediment pins installed at project construction in August 1994 and three DEMs for March 1997, September 1998, and August 1999. DEM baseline elevation assumed to be 0.0m NAVD. Sediment pin SP-5 was located within a depression that evolved into a naturally formed channel and thus has lower elevations yet similar accretion rates.

5.4 DEM Sediment Volume and Mass Net Accretion

The purposes of using the DEMs to calculate sediment accretion are (1) to derive a high resolution image for evaluating spatial patterns of net accretion, (2) to explore outcomes on the marsh plain and channel evolution and structure in support of improving our understanding of geomorphic processes, and (3) to compare to other methods of estimating sediment influx for overall quality control amongst these various methods.

5.4.1 Bulk Density

Table 5-1 presents sediment bulk density data prepared by students in the UC Berkeley Geography field course in Spring 1997 based on one core sample analyzed at various depths.

Table 5-1. Sediment Bulk Density for One Core Sample, March 1997

Sample Depth (cm below ground surface)	Bulk Density (g cm ⁻³)
0	1.24
20	1.19
40	1.14
60	1.15
70	1.23
80	1.23
Mean	1.20

Notes:

1. Sediment core collected 8 March 1997
2. All samples extracted from one sediment core
3. All samples are of post-restoration deposited sediments

Estuarine mineral soil bulk densities typically range between 1.0 and 2.0 g cm⁻³ in wetland soils (Mitsch and Gosselink 2000). This core sample was collected when site elevations were low enough that most every high tide inundated the entire site surface and hence the soils were subjected to a minimum of exposure-induced consolidation processes. No data were collected at later dates when site elevations had increased. Bulk density data from the naturally formed Hoffman Marsh in Richmond, California reached a maximum of 1.62 g cm⁻³ on pickleweed (*Salicornia virginica*)-vegetated tidal marsh (Machado 1985). Surface soils at Hoffman Marsh were readily capable of supporting the weight of a human with minimal sinking into the sediments, whereas field observations during this field study confirmed that at no time did study site sediments reach strengths sufficient to support the weight of a human (though after completion of this field work, some areas can support weight of humans). Based on these data, I have used 1.20 g cm⁻³ as the bulk density for calculating sediment mass from baseline to March 1997, and an estimated value of 1.50 g cm⁻³ for the two subsequent calculations. This latter estimated value introduces uncertainty into the mass calculations shown in Table 5-2.

5.4.2 Net Volumetric and Mass Accretion

From the three DEMs I have calculated the volumetric difference during the period monitored and estimated volumetric changes from initial conditions assuming a

baseline elevation of MLLW (derived from limited sediment pin and project sponsor-provided topographic data). Table 5-2 presents the volumetric and mass accretion data calculated from the three DEMs, assuming baseline elevations at MLLW (see baseline elevation determination in Section 3.2.1), and using measured bulk density values presented in Table 5-1. Table 5-2 also includes an uncertainty estimate of the calculated mass values for the latter two periods assuming a bulk density uncertainty of $\pm 0.30 \text{ g cm}^{-3}$ (i.e., the range of 1.20 to 1.80 g cm^{-3}). Table 5-2 presents net sediment accretion rates measured in two ways: cumulative (from baseline to time of measurement); and incremental (from one measurement to the next). Figure 5-6 shows these data from Table 5-2 graphically.

These data show that approximately 80% of the total accumulated sediment from the time of restoration in August 1994 to the most recent measurement in August 1999 occurred during the first 2.6 years, nearly all the remaining 20% accumulated from years 2.6 to 4.1, and virtually no additional accretion occurred from years 4.1 to 5. The baseline to 1997 measurement assumes a starting elevation of 0m based on the sediment pin data shown in Section 5.3. Translating these data to accretion rates (Table 5-2 parts B and C) reveals the general pattern of high accretion rates when the site elevation is low and lower accretion rates once elevations have increased, which reduces tidal submergence duration.

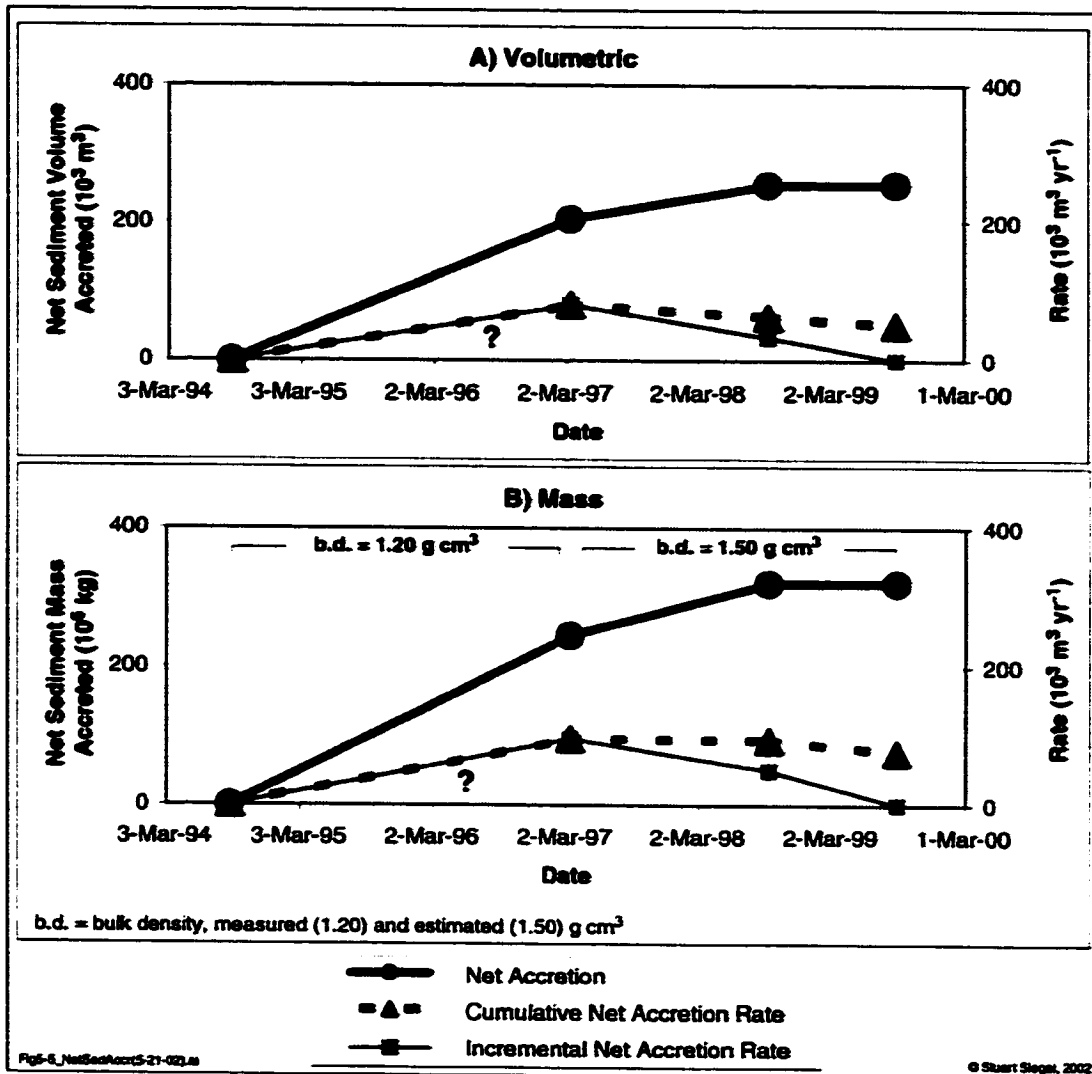
Table 5-2. Net Sediment Accretion from DEMs and Bulk Density Estimates

DEM	Years 0-2.6		Years 2.6-4.1		Years 4.1-5.0	
Statistics ¹	Aug 1994 to Mar 1997 ^{2,3}		Mar 1997 to Sep 1998 ³		Sep 1998 to Aug 1999 ³	
A) Net Sediment Increases⁴						
	(10 ³ m ³)	(10 ⁶ kg)	(10 ³ m ³)	(10 ⁶ kg)	(10 ³ m ³)	(10 ⁶ kg)
Mean	204	245	50	75	0.14	0.22
Median	205	245	50	75	0.13	0.19
SD	0.4	0.5	0.2	0.4	0.03	0.05
CV	0.2%	0.2%	0.5%	0.5%	24%	24%
Mass uncertainty (±10 ⁶ kg) ⁵					15	0.05
B) Cumulative Net Sediment Accumulation Rates⁶						
	(10 ³ m ³ yr ⁻¹)	(10 ⁶ kg yr ⁻¹)	(10 ³ m ³ yr ⁻¹)	(10 ⁶ kg yr ⁻¹)	(10 ³ m ³ yr ⁻¹)	(10 ⁶ kg yr ⁻¹)
Mean	80	96	63	94	51	76
Median	80	96	63	94	51	76
SD	0.4	0.5	0.2	0.4	0.03	0.1
CV	0.5%	0.5%	0.4%	0.4%	0.1%	0.1%
Mass uncertainty (±10 ⁶ kg) ⁵					20	15
C) Incremental Net Sediment Accumulation Rates⁷						
	(10 ³ m ³ yr ⁻¹)	(10 ⁶ kg yr ⁻¹)	(10 ³ m ³ yr ⁻¹)	(10 ⁶ kg yr ⁻¹)	(10 ³ m ³ yr ⁻¹)	(10 ⁶ kg yr ⁻¹)
Mean	80	96	33	50	0.15	0.23
Median	80	96	33	50	0.13	0.20
SD	0.4	0.5	0.2	0.4	0.034	0.052
CV	0.5%	0.5%	0.7%	0.7%	23%	23%
Mass uncertainty (±10 ⁶ kg) ⁵					10	0.05

Notes:

1. Five DEM generation settings were used to assess DEM variance.
2. Aug 1994 (restoration start) to 1997 assumes flat baseline surface at 0.0 ft/m NAVD.
3. Bulk density values of 1.20 g cm⁻³ used for years 0-2.6 and 1.50 g cm⁻³ for subsequent two periods
4. Volumes derived from cut-fill differences between each DEM.
5. Mass calculation uncertainty based on bulk density range of 1.20 to 1.80 g cm⁻³ for later two periods.
6. Cumulative sedimentation rate = total volume/elapsed time.
7. Incremental sedimentation rate = volume between measurements/time between measurements.

Figure 5-6. Net Sediment Accretion versus Time, from DEMs



Volumetric accretion (panel A) shows the temporal change in site volumes calculated by DEM elevation differences. Represents filling of the site's tidal prism. Mass accretion (panel B) uses bulk density values to convert volume data from panel A into mass values. Shape of accretion rate lines both plots unknown between project start and first topographic data set 2.6yr later.

5.5 Sediment Grain Size Characteristics

I collected surface sediment samples to determine grain size characteristics of the sediment deposited at the site. Grain size characteristics, in turn, influence the physical and chemical behavior of the deposited sediment (Mehta 1993, Eisma 1998, Black *et al.* 1998). Table 5-3 presents the grain size data. Field observations early in the research indicated very uniform sediment characteristics throughout the site, so the grain size data should approximate the suspended sediment load in the tides.

Table 5-3. Surface Sediment Grain Size Distribution

Sample ID ¹	Sample Date	Total Sample Fractions ^{2,3,4}				Median Size (um)
		% Gravel	% Sand	% Mud		
				% Silt	% Clay	
SM 1	29-Mar-99	0.00	0.84	25.0	74.2	1
SM 2	29-Mar-99	0.00	0.91	23.2	75.9	1
SCN	29-Mar-99	0.00	0.77	26.7	72.5	1
SCN(F)	29-Mar-99	0.00	0.75	26.9	72.4	1
SC	29-Mar-99	0.00	0.40	54.0	45.6	4

Notes:

1. SM = South Mudflat station;
SCN = South Channel, North of SC Station
SC = South Channel station
2. Laboratory analyses performed by U.S. Geological Survey, Menlo Park, CA.
3. Samples analyzed by laser particle size diffraction method.
4. Samples represent top 2 cm of sediment.

The sediments at the site are more than 99% mud. Four of five samples were about 25% silt and 75% clay with a median grain size of 1µm and the fifth sample was

roughly 50/50 silt and clay with a median grain size of 4 μ m. Sand composed from 0.4 to 0.9% of the samples.

5.6 A Model for Mudflat/Marsh Plain Accretion Patterns

Formation of a marsh plain within a spatially confined diked, subsided bayland represents a different mode of marsh evolution relative to how existing tidal marshlands have formed in the San Francisco Estuary and elsewhere (lateral inland spread into drowned river valleys during sea level rise and lateral bayward spread onto mudflats during high sediment load periods). Consequently, a new model of marsh accretion is necessary help elucidate temporal and spatial patterns of mudflat/marsh plain accretion in the early stages of opening a diked, subsided bayland to tidal action.

The “prograding delta” model of fluvial geomorphology offers a promising starting point because of many parallels, even though it originates from a different hydrologic regime. In the fluvial context, sedimentary deltas often form at the mouth of a stream where it drains from a confined channel onto an open plain, be it in a mountain valley or a coastal setting (Leopold *et al.* 1964, Steers 1971, Kelletat 1995). As deposition progresses, the delta progrades farther onto the plain and gives this model its name.

In a restored diked bayland, the levee breach acts as the initial “confinement” throughout a flood tidal cycle. Once through the breach, tides open into a broad

“plain” onto which sediment deposits as shear velocities drop below critical suspension values (Dronkers and van Leussen 1988, Mehta 1993, Black *et al.* 1998, Eisma 1998). The sudden drop in velocities just inside the breach leads to a proportionally greater deposition nearest the breach. This gradient is not large, however, because the low settling velocities of fine-grained estuarine sediments allow transport further into the site (Collins *et al.* 1987, Leopold *et al.* 1993, Mehta 1993, Eisma 1998).

As the mudflat/marsh plain accretes inside the levee breach, it progressively contributes to the “confinement” of flood tide for a greater percentage of a flood tide, thereby shifting the position of the initial velocity drop further into the basin during early flood tide stages. As the tide rises and overtops the accreting mudflat/marsh plain, then the breach again becomes the primary point of velocity declines. Higher elevations brought about by accretion reduce the inundation duration and thus deposition period. Thus, as the site accretes near the breach, the location of peak deposition shifts spatially into the site from the levee breach.

Complicating this simple hydraulic perspective is the time-varying nature of suspended sediment concentrations. Deposition rates depend on SSC, so the time during the flood tidal cycle at which SSC reaches its maximum would correspond to the greatest deposition rates under identical hydraulic conditions. The time series SSC data (Appendix B) reveal that peak SSC values tend to occur in the middle and later periods of the flood tide cycle rather than at the very earliest stages. These conditions

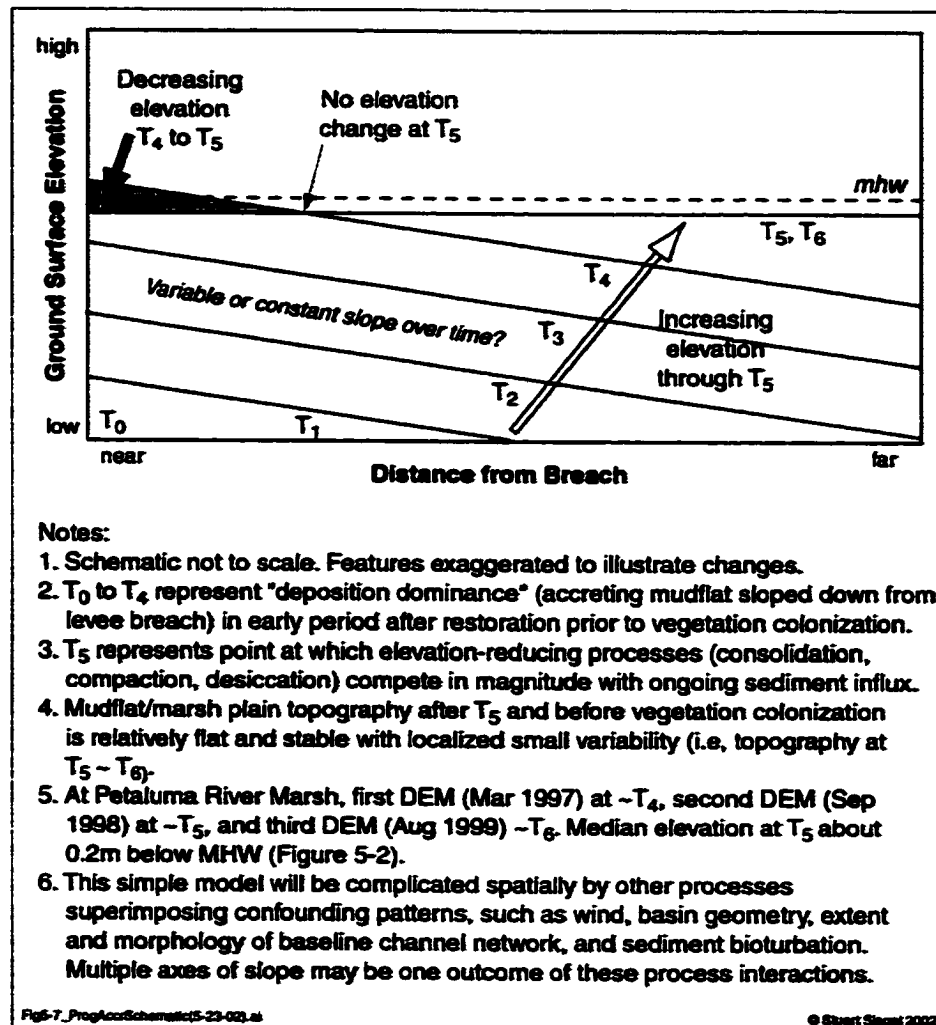
derive from tidal current transport of sediment entrained from nearby San Pablo Bay mudflats, with the lag time to peak concentration relating to the distance the estuarine turbidity maximum must travel to reach the site (Schoellhamer 1995; Schoellhamer, personal communication, 2001). Spring tides and summer winds generate greater SSC values relative to neap tides and lower-magnitude winter winds (Schoellhamer, personal communication, 2001). The implications of time-varying SSC is that the locations of peak deposition within the site then depend not only on position of velocity drops as a function of tidal stage but also on available sediment supply as a function of tidal stage. The time lag for peak flood tide SSC values increases the frequency with which maximum SSC coincides with that velocity drop occurring closer to the levee breach, thereby promoting deposition closer to the breach and reinforcing the prograding delta concept.

5.6.1 Model Predictions

This “diked bayland restored marsh plain geomorphic evolution” model states that sediment accretion progresses as a “wave” from the breach toward the distal end of the sedimentary basin (angled lines labeled T_1 through T_4 in Figure 5-7). At the start of restoration (T_0), the subsided site is low and probably relatively flat. At any given point during the prograding period, there exists a slope to the deposited mudflat surface along this breach-distal basin axis. At some point, this wave reaches the distal end of the basin and the prograding period comes to its conclusion (T_5). At this point,

the relative importance increases of processes other than deposition on affecting site topography, namely consolidation and desiccation (Eisma 1998, Allen 2000b), even while sediment influx and deposition continues.

Figure 5-7. Diked Bayland Restored Mudflat/Marsh Plain Geomorphic Evolution Model Prior to Vegetation Colonization



These general patterns would be expected to occur at any restoration site regardless of size (small sites perhaps excepted). However, larger restoration sites typically

introduce more confounding variables. The need to provide sufficient tidal and sediment exchange can often lead to restored hydrologic regimes far more complex than that at this study site. More complex hydraulics would presumably replicate the general concepts of the prograding delta model yet their effects on accretion rates would have a more complex picture. Other baseline conditions of a restoration site would also affect application of this model, such as site orientation to prevailing winds, starting elevations, incorporation of flow barriers, and so forth.

One key element of this model prediction is that it anticipates topographic gradients rather than horizontal slopes across a restored diked bayland. Though these gradients are small by fluvial terms, very small changes in elevation (on the order of centimeters) can influence site ecology directly through inundation regime and indirectly through soil chemistry properties (Mitsch and Gosselink 2000, Weinstein and Kreeger 2000, French and Reed 2001, Zedler 2001).

5.6.2 Transition from Deposition Dominance

Net accretion integrates processes that increase elevation (deposition prior to plant colonization, deposition and biomass accumulation after plant colonization) and those that decrease elevation (compaction, consolidation, desiccation); see Figure 2-3 in Chapter 2.

Consolidation and desiccation act most strongly on the highest elevation mudflat surface, so the highest areas at the end of the prograding period could drop in elevation. Some areas may have no net change in elevation. And some areas may continue to rise. The inverse relationship between elevation and accretion rates defines the “top” of the prograding delta and thus influences the transition timing out of the prograding delta period. The mudflat/marsh plain should have fairly flat topography at the conclusion of the prograding delta period. At that point in time, continued accretion has a strong biological control via plant colonization, as vegetation helps to trap suspended sediment, it produces peat, and it partially shields the ground surface from wind and sun desiccation (French and Spencer 1993, Turner *et al.* 2000, Eisma 1998, Allen 2000b, French and Reed 2001).

5.6.3 Evidence for Model

What evidence does the data presented in this and preceding chapters provide to support or reject this model? The answer lies in Map 4-8 (topography each year), Map 5-1 (topographic change between years), Figure 5-2 (topographic data vertical distribution), Figure 5-3 (accretion rates), Figure 5-4 (elevation vs. accretion rates), and Figure 5-1 (net sediment influx). These data, discussed below, describe a natural system complete with its variability; consequently, these data can offer general support for or rejection of this model but will also include exceptions each of which may or may not have an explanation that supports or rejects the model.

The South Basin topographic gradient in 1997 from the levee breach downward to the headward (northern) reaches of that basin is well illustrated in Map 4-8A. The North Basin gradient is not as closely associated with the levee breach as is the case for the South Basin, instead being oriented more in a south (high) to north (low) direction. At high tides when water crosses between the North and South Basins at the western tip of the central levee, the site acts in part as an extension of the Petaluma River, with flood tides flowing in the South Breach and out the North Breach and ebb tides doing the opposite. Once below the drainage divide elevation, each basin operates as an independent hydrologic basin. The lower the elevation, the greater duration the two basins are connected. This topographic control means that in the early period following restoration the basins were often connected and that connection duration diminished as the site rapidly accreted. At 2.6 years after restoration at the time of the first DEM, the site had already accreted about 75-80% of the sediment that it had accreted through the end of the study in 1999 at 5 years post restoration (Table 5-2, Figure 5-2). These spatial topographic gradients in 1997 indicate that the site was still within its “prograding delta” period, approximately at T_4 in Figure 5-7.

Map 5-1 shows the elevation changes over time. The period from March 1997 to September 1998 (Map 5-1A) captured the final accretionary period prior to the site converting to a period of near stasis in its topography (Map 5-1B). The areas of greatest sediment accretion from 1997 to 1998 (shown as green areas in Map 5-1A) in the South Basin are located in the furthest reach of the basin where the final stage of

prograding delta was accreting sediment, along the pilot channel where overall channel volume was declining, and the very southeast corner of the South Basin where the prevailing northwesterly summer winds push sediment-laden water. A similar pattern exists for the North Basin, with the basin divide acting as the sediment source.

In contrast, the period from September 1998 to August 1999 (Map 5-1B) shows an entirely different spatial pattern of deposition. For most of the site, very little change occurred, with much of the site falling within the range of methodological uncertainty ($\pm 0.07\text{m}$) and hence zero quantifiable change. The two locations that exhibited more than minimal accretion were just inside the South Breach and the very northern end of the North Basin. The South Basin accreting area appears to represent an ongoing filling of the channel network, presumably a decline in channel capacity in response to decreasing tidal prism. The North Basin accreting area balances a similar-sized area with declining elevations, with a boundary between the two of no definitive change. The dropping area corresponds to the highest elevations in 1998 and the rising area corresponds to lower areas in 1998 (Map 4-8B in Chapter 4). By August 1999, this North Basin gradient had reversed direction, largely leveling the area but with a distinct higher area in 1999 that had been lower in 1998. These data align well with “T₅” changes suggested by Figure 5-7, with some areas rising, some dropping, and an inflection point of no change.

5.6.4 Limitations to the Interpretation

Accretion patterns between restoration and year 2.6 when this research began are not known. Some aerial photography exists for that interval, but none are stereo-pair necessary for quantifying topography. Consequently, whether the site exhibited surface gradients consistent with the prograding delta model is not known. Data for the March 1997 DEM (Map 4-8A) fortunately were collected within what appears to be the prograding delta period.

5.7 Feedback between Elevation-Sedimentation-Desiccation

Several pieces of the data presented in this chapter point to a feedback mechanism between ground surface elevation, sedimentation, and desiccation. Such feedback is anticipated (Eisma 1998, Callaway 2001) and these data provide a high-resolution quantification of these mechanisms.

5.7.1 Sedimentation Rates as a Function of Elevation

In a tidal environment, higher elevations are subject to decreased tidal submergence – depth, duration, and, once elevations exceed the lowest high tide level (about 0.5m below MHW at this site; Figure 5-1), frequency. Sedimentation can only take place when the ground is submerged, and the greater amount of submergence the greater

potential for sedimentation, translating to the expectation that lower elevations should accrete more rapidly and as sedimentation proceeds its rate should decline. The data presented in Figure 5-4 clearly establish that relationship at the study site.

5.7.2 Ground Surface Elevation and Desiccation

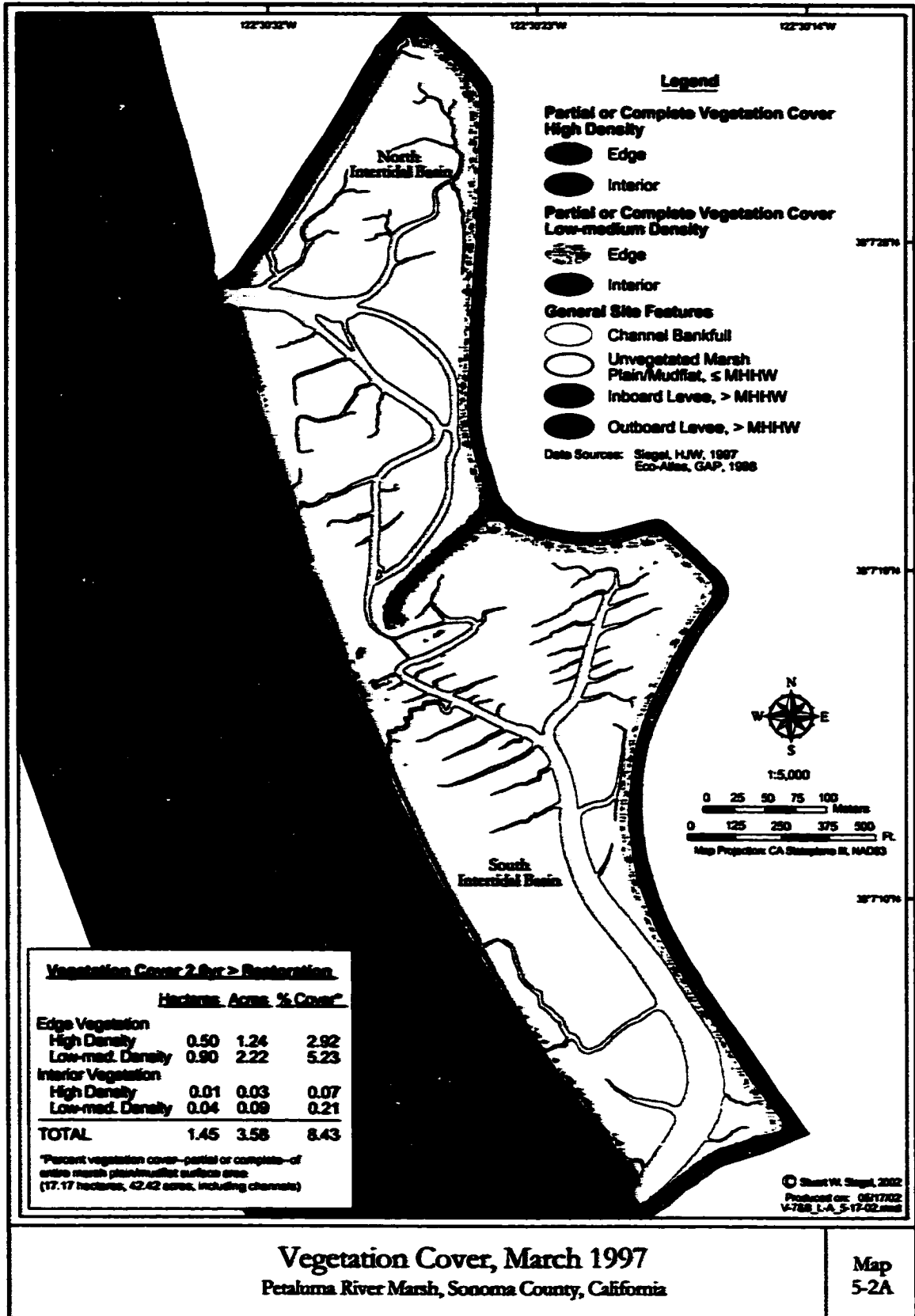
As elevations increase, the ground surface is exposed to the open air with increasing duration, allowing sun, wind, and warm temperatures to evaporate water from the sediments. Evaporation has a cascade effect, first desiccating the sediments, which lead to their compaction and hence increased bulk density, which translates finally into a lowered ground surface elevation (Mehta 1993, Brady and Weil 1996, Eisma 1998). Consolidation of settled particles also takes place, further increasing bulk density and decreasing elevations. These processes counteract sedimentation and become increasingly important concurrent with decreasing sedimentation rates associated with higher elevations (Black *et al.* 1998, Eisma 1998, Allen 2000b, Callaway 2001, French and Reed 2001, Figure 2-3 in Chapter 2).

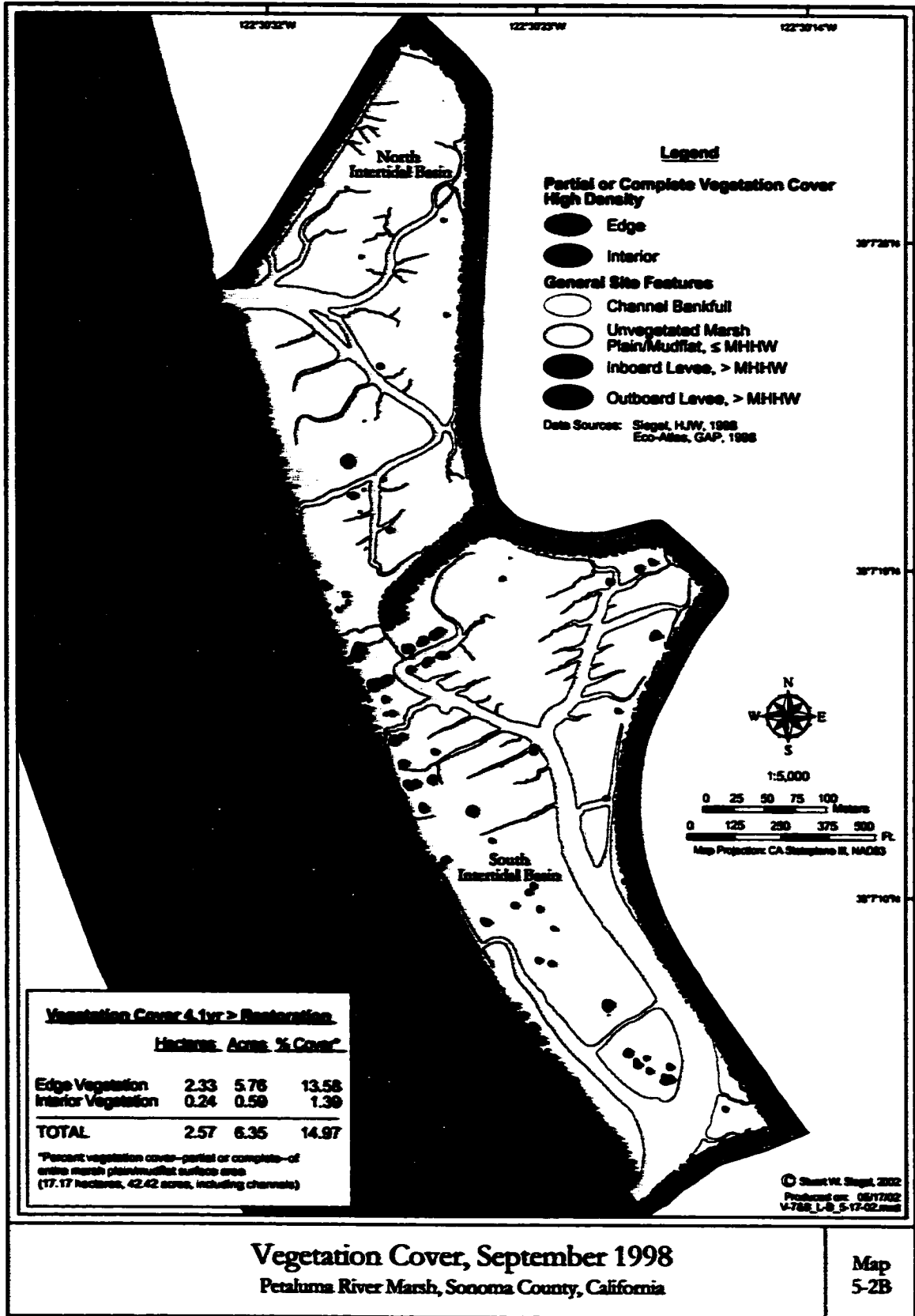
In the San Francisco Estuary, there exists a seasonal reversal in the time of day at which the lower low tide occurs. At present, most lower low tides occur during the daytime in the hot and windy summer, providing optimum conditions for maximum desiccation. Lower low tides typically occur at night in the winter, a condition that minimizes desiccation potential. Malamud-Roam (2000) determined that this pattern

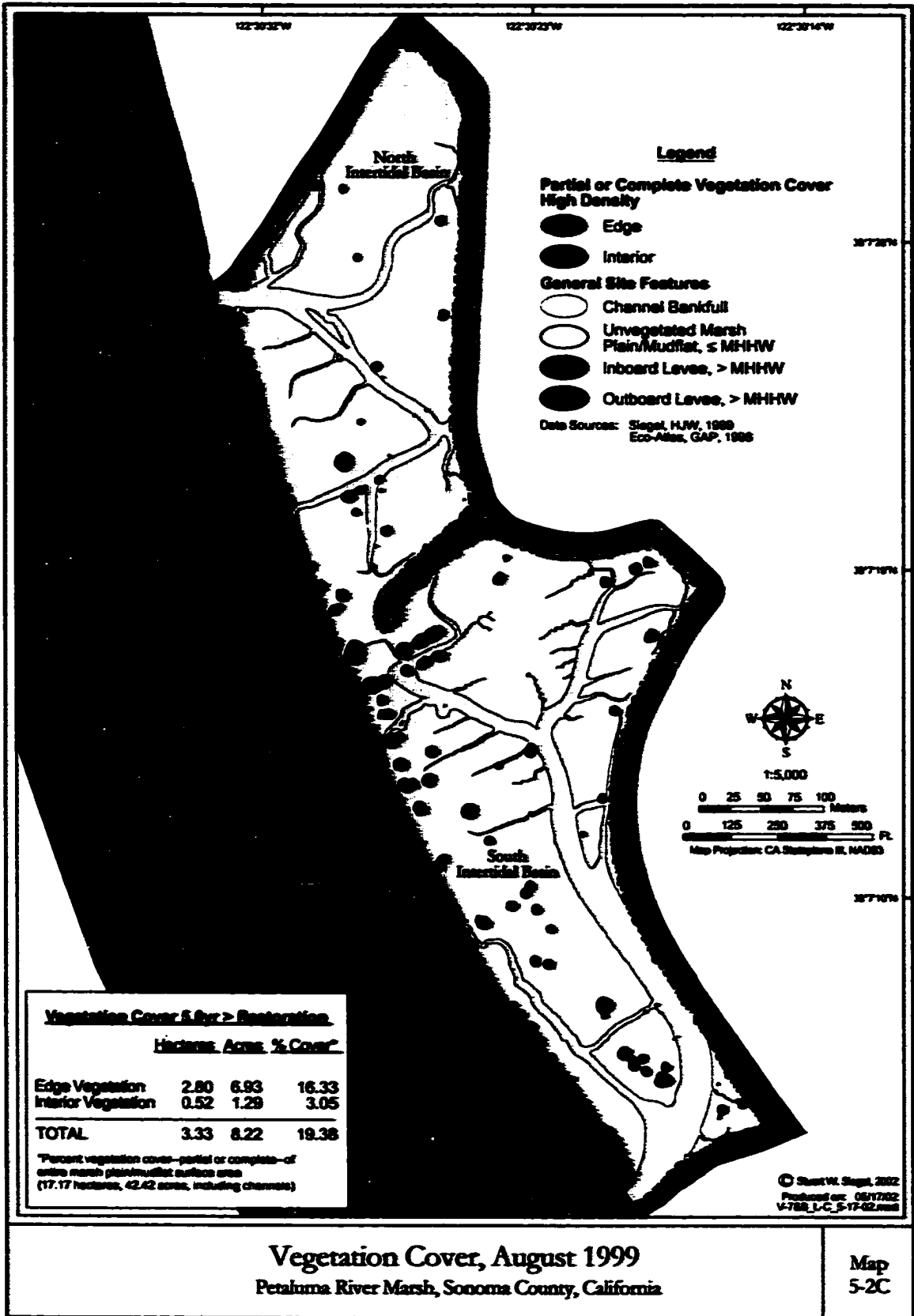
repeats on an approximately 300-year cycle, meaning the opposite conditions applied at the time of the California gold rush when tidal marsh “reclamation” began in the region. The current tidal regime maximizes the effect of the desiccation process on any marsh restoration project in the Estuary.

5.7.3 Vegetation Influence on Sedimentation and Desiccation

The presence of vegetation will alter sedimentation and desiccation processes. Previous research has established the positive relationship between marsh vegetation and increased sedimentation rates (e.g., French and Spencer 1993, French *et al.* 1995a). Thus, once vegetation colonization has begun, sedimentation around the plants themselves should increase relative to unvegetated areas of the same elevation. During the study period, very little vegetation had colonized the site and most of that colonization occurred around the site perimeter (Map 5-2). Consequently, this research did not need to collect data to evaluate that relationship. Vegetation will also shade the ground surface and shelter it from the wind, reducing their effects on desiccation. Conversely, the vegetation itself will lead to evapotranspiration, thereby removing soil moisture and promoting compaction. The potential for evapotranspiration to influence soil moisture in a tidal marsh therefore depends on elevation through its effect on vegetation composition and inundation regime (Mitsch and Gosselink 2000, Weinstein and Kreeger 2000).







Vegetation colonization in restored diked baylands occurs once elevations have risen to a minimum height to provide the inundation regime suitable for vegetation survival and growth. Inundation regime is the indicator of colonization and establishment through its controls on soil aeration, soil moisture, soil salinity, temperature, and light characteristics (Mahall and Park 1976c, Keddy and Ellis 1985, Ungar 1991, Mitsch and Gosselink 2000). Survival and growth once plants have colonized are affected by a variety of abiotic factors just mentioned along with biotic factors such as competition, herbivory, and ecotypic, genotypic, and phenotypic variability (Fenner 1985, Jefferies and Rudmik 1991, Baye *et al.* 2000).

The vegetation cover shown in Maps 5-2A through 5-2C show vegetation colonization around the site perimeter in the early period, corresponding to higher elevations suitable for early vegetation establishment, and very limited interior colonization. A very small numbers of plants (0.3% cover) had colonized the site interior by March 1997 (Map 5-2A). By September 1998 (Map 5-2B) additional interior colonization had occurred along with lateral expansion, raising interior plant cover to 1.4%. By August 1999 (Map 5-2C) the interior plants had increased in cover to 3.0%, still a low relative cover. Median marsh plain elevations were about 0.2m below MHW between September 1998 and August 1999, suggesting a lower elevation at which conditions became suitable for natural (unassisted by human intervention) vegetation establishment.

5.7.4 Relevant Elevations at Which Feedback Shifts Net Accretion Mode

The final question that remains is at what elevation does the site shift accretion modes from a rapidly accreting tidal basin to an intermediately stable ground surface elevation at which accretion from ongoing sediment influx is offset with elevation declines brought about by consolidation, compaction, and desiccation (see Figure 5-7)? The mechanism by which this shift occurs is that the site reaches an elevation at which the effectiveness of elevation-reducing processes matches or exceeds the rate of ongoing inundation-controlled sediment deposition. At the study site, this transition occurred in advance of any significant vegetation colonization.

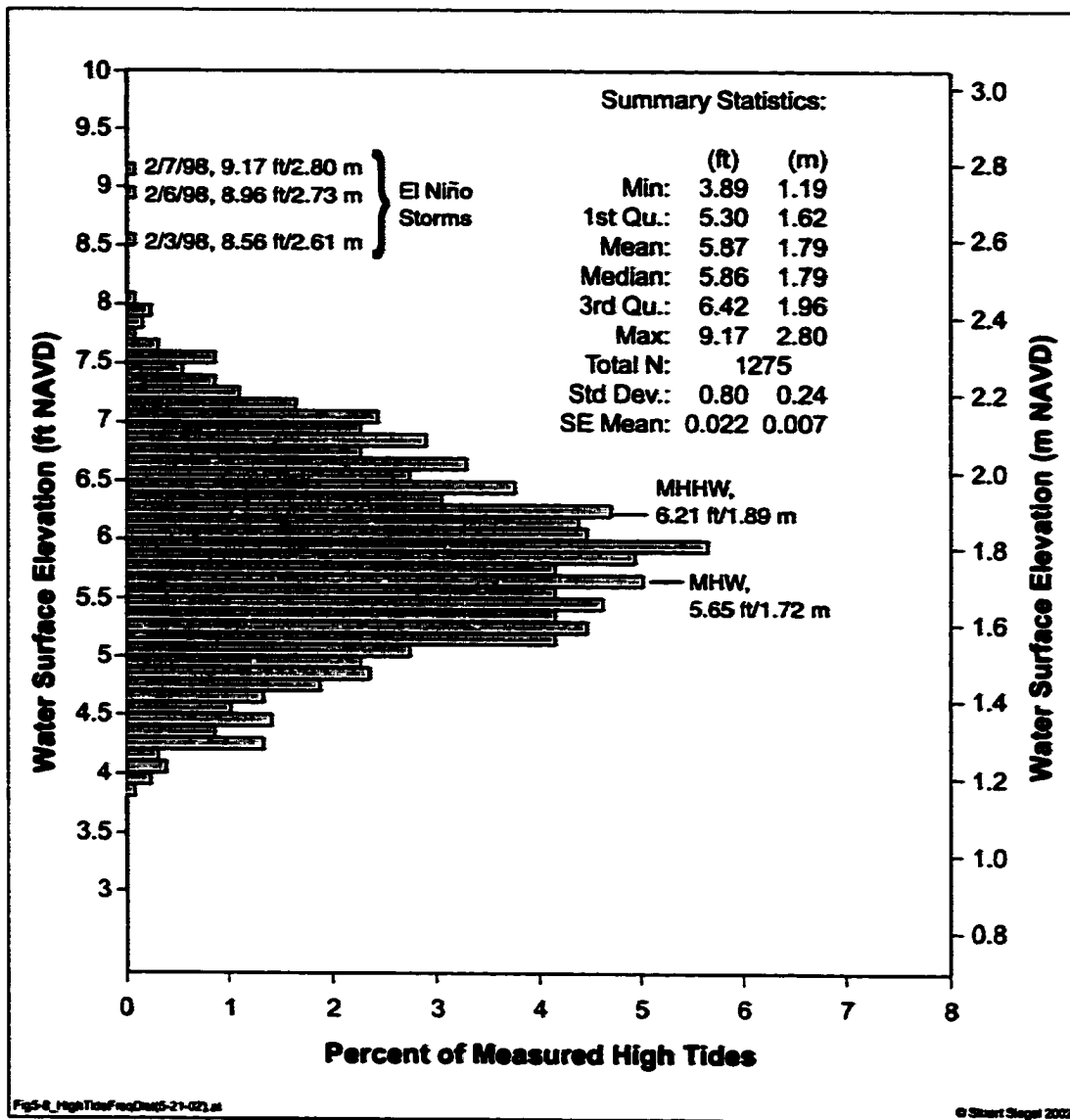
The answer appears to lie in the topographic data distribution shown in Figure 5-2; namely, about 0.2m below local mean high water which corresponds to submergence by about 90% of the high tides during the study period (Figure 3-1 in Chapter 3). Median site elevations reached this elevation by September 1998 and remained essentially unchanged through August 1999. This elevation approximately corresponds to the height at which tidal salt marsh species are able to colonize and spread effectively on the accreted mudflat/marsh plain surface. Post-1999 vegetation colonization has been considerable, as documented in the 2000 and 2001 aerial photographs (Maps 4-3B and 4-3C in Chapter 4).

5.8 Extreme Events and the 1998 El Niño

The 1997-1998 El Niño event was of large magnitude. During the 2.5-month period from December 1997 to February 1998, about 0.15m (0.5ft) of sediment accumulated at the research site (Figure 5-6). The three largest tide events during the study period and probably (though not confirmed) since the 1982-83 El Niño event occurred over a 4-day period in February 1998, ranging from 0.7-0.9m (2.4-3.0ft) above MHHW (Figure 5-8).

The net sediment influx during this El Niño event was the largest observed during the study period (Figure 5-1A). The major storm events captured in Figure 5-8 are also visible in the time series plot of the height of each successive high tide shown in Figure 5-1B. These data emphasize the importance of stochastic events in tidal marsh restoration evolution, a factor that some researchers have suggested be accounted for in design (e.g., Day *et al.* 2000).

Figure 5-8. Frequency Distribution of High Tide Magnitudes



This figure shows frequency distribution of measured high tides from January 1998 to November 1999. Mean high water (MHW) and mean higher high water (MHHW) datums are shown. Three peak tide events occurred over five days in February 1998 during El Niño storms. Mean water level was 0.07m above MHW during the study period, with temporal patterns evident in Figure 5-1.

Chapter 6.0 Role of Initial Conditions

The purpose of this chapter is to examine the question of *how initial geomorphic conditions influence the geomorphic evolution of the channel network and the adjacent developing tidal marsh plain*. Improving our general understanding of the role of initial conditions can aid in tidal marsh restoration design by informing the possible evolutionary trajectories that a site may experience following restoration.

Data used to evaluate this question include the digital elevation model (DEM) results, field-collected topographic data, and water column suspended sediment concentrations and net fluxes presented in Chapter 5 (Figure 5-1). Indicators of initial condition effects are divided into five types presented in Sections 6.1 through 6.5 and are discussed in Sections 6.6 and 6.7:

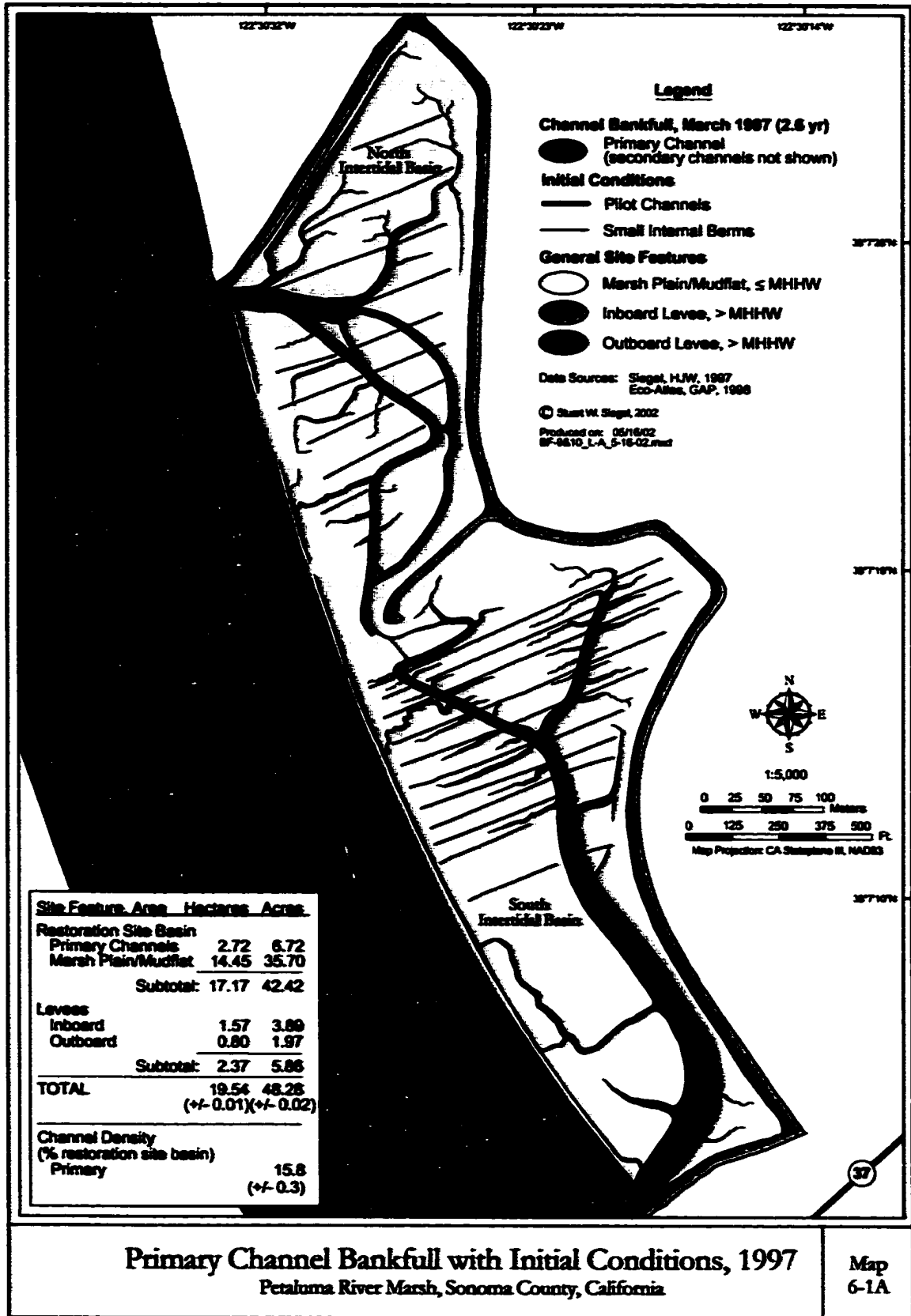
- **Channel planform morphological evolution** (Section 6.1) informs restoration design by evaluating persistence of pilot channels and borrow ditches and examining the extent to which lateral migration may occur, all in response to an initial rapidly accumulating sedimentary environment.
- **Cross sections** (Section 6.2) reveal evolution of at-a-station channel geometry that in turn provide insight into how channels evolve. These data can inform restoration design by providing insight into what degree of initial constructed geometry may be appropriate to promote target channel geometry.

- **Longitudinal profiles along the pilot channels** (Section 6.3) show the evolution of channel depth over time and how it responds to infilling sediment and decreasing tidal prism (volumetric tidal exchange). These data can inform restoration design efforts through improving our understanding of minimum channel elevations and their response to initial conditions and tidal prism.
- **Channel network evolution from initial conditions** (Section 6.4) presents a wealth of quantitative data about the channel networks for each year, offering several views of these patterns. The channel network is one of the most fundamental components of a natural tidal marsh system and the extent to which natural processes in a restoration site promote formation of an extensive channel network carries clear restoration design implications.
- **Channel formation and small parallel berms** (Section 6.5) evaluates how the simple, non-engineered berms that were part of post-construction initial conditions affected formation of natural channels outside the constructed pilot channels.
- **Primary channel formation and initial conditions** (Section 6.6) discusses mechanisms for how small parallel berms can promote natural channel formation.

- **Secondary channel formation and shallow mudflat ebb flows (Section 6.7)** discusses mechanisms that lead to secondary channel formation and that these mechanisms are not affected by initial conditions.

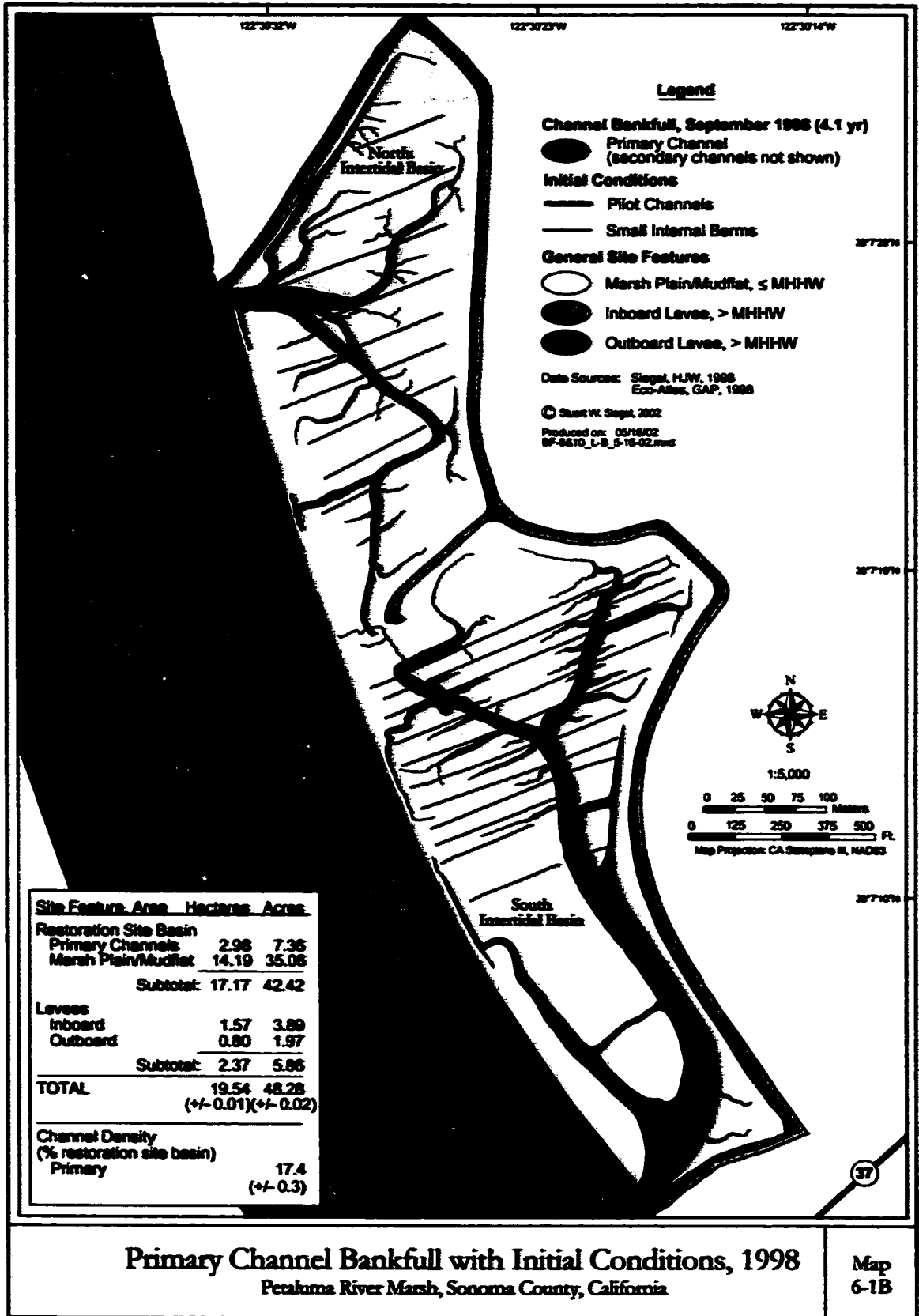
6.1 Channel Planform Morphology

I digitized channel planform morphology for each period (March 1997, September 1998, and August 1999) from the aerial photographs and from DEM-generated contour lines (see Figure 4-2 in Chapter 4). Map 6-1 shows channel morphology for the primary channels (i.e., larger channels) for each period. This map also shows locations of the small berms and pilot channels created as part of construction in order to visualize the relationship between these initial conditions and resultant channel planform morphology. Map 6-2 shows channel morphologic change between years and includes the secondary channels (i.e., small channels). In this change detection map, black represents areas common to each year in the comparison, blue indicates areas of channel expansion (headward and lateral), and red shows areas of channel contraction (bayward and lateral).



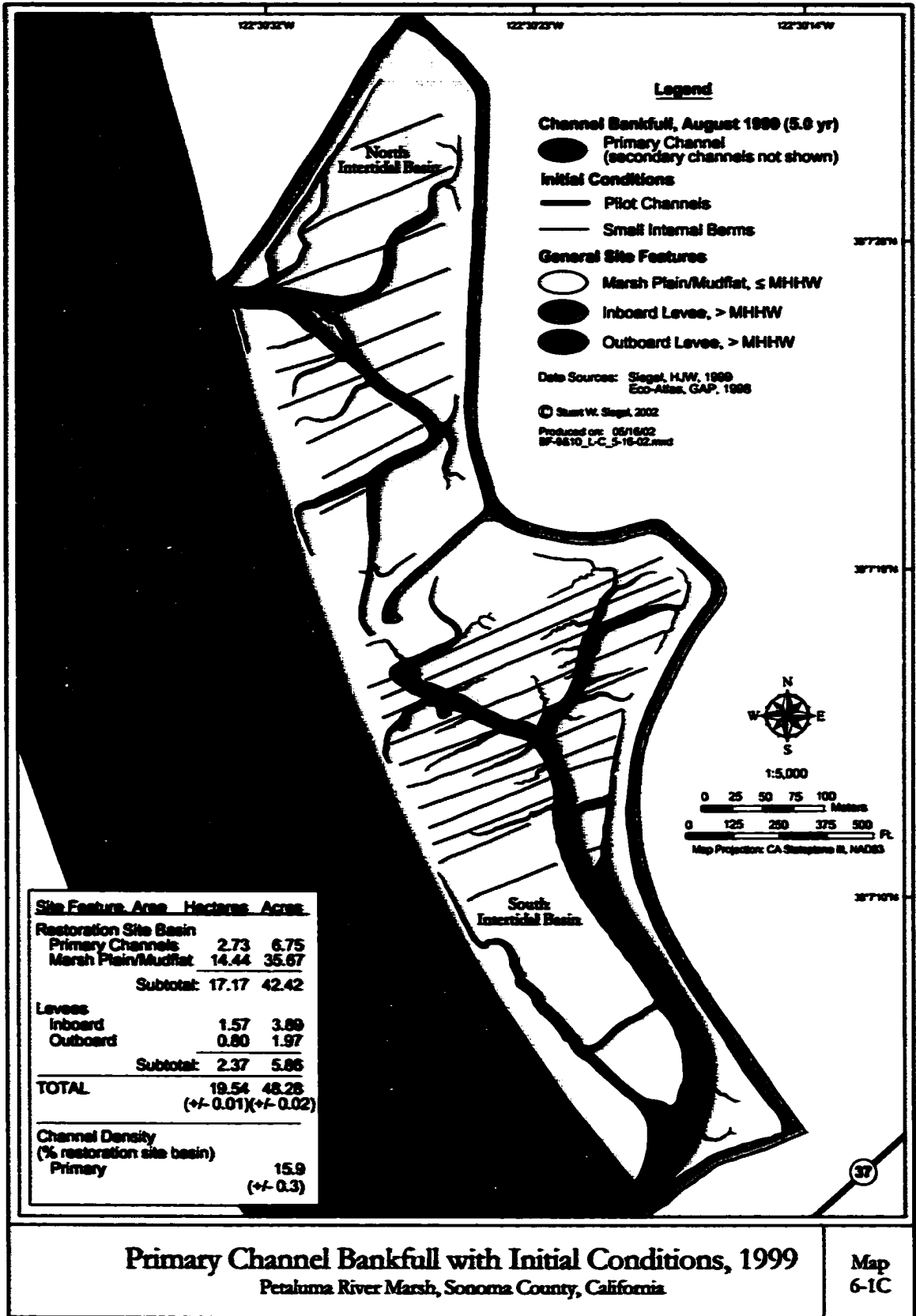
Primary Channel Bankfull with Initial Conditions, 1997
 Petaluma River Marsh, Sonoma County, California

Map
 6-1A



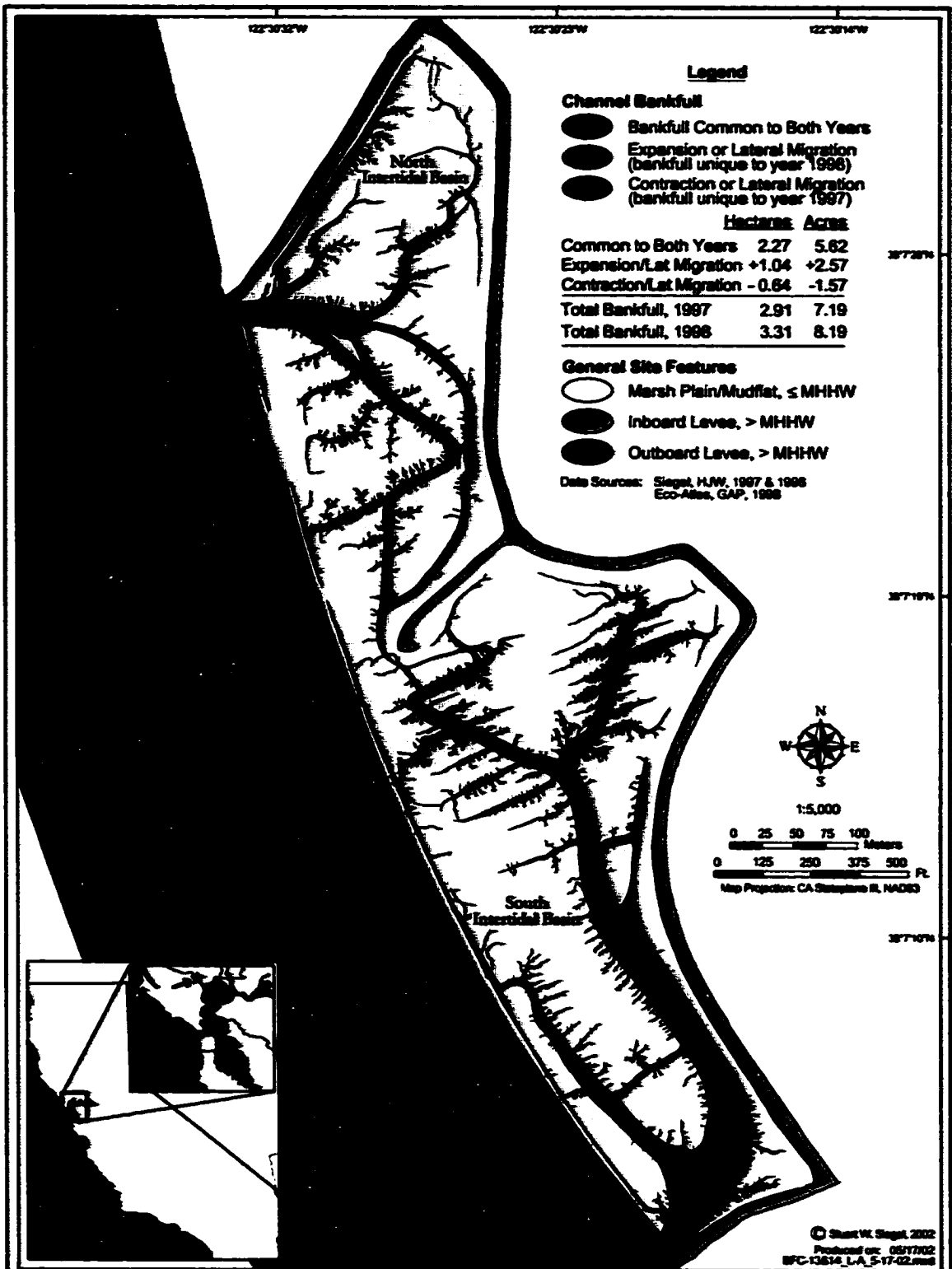
Primary Channel Bankfull with Initial Conditions, 1998
Petaluma River Marsh, Sonoma County, California

Map
6-1B



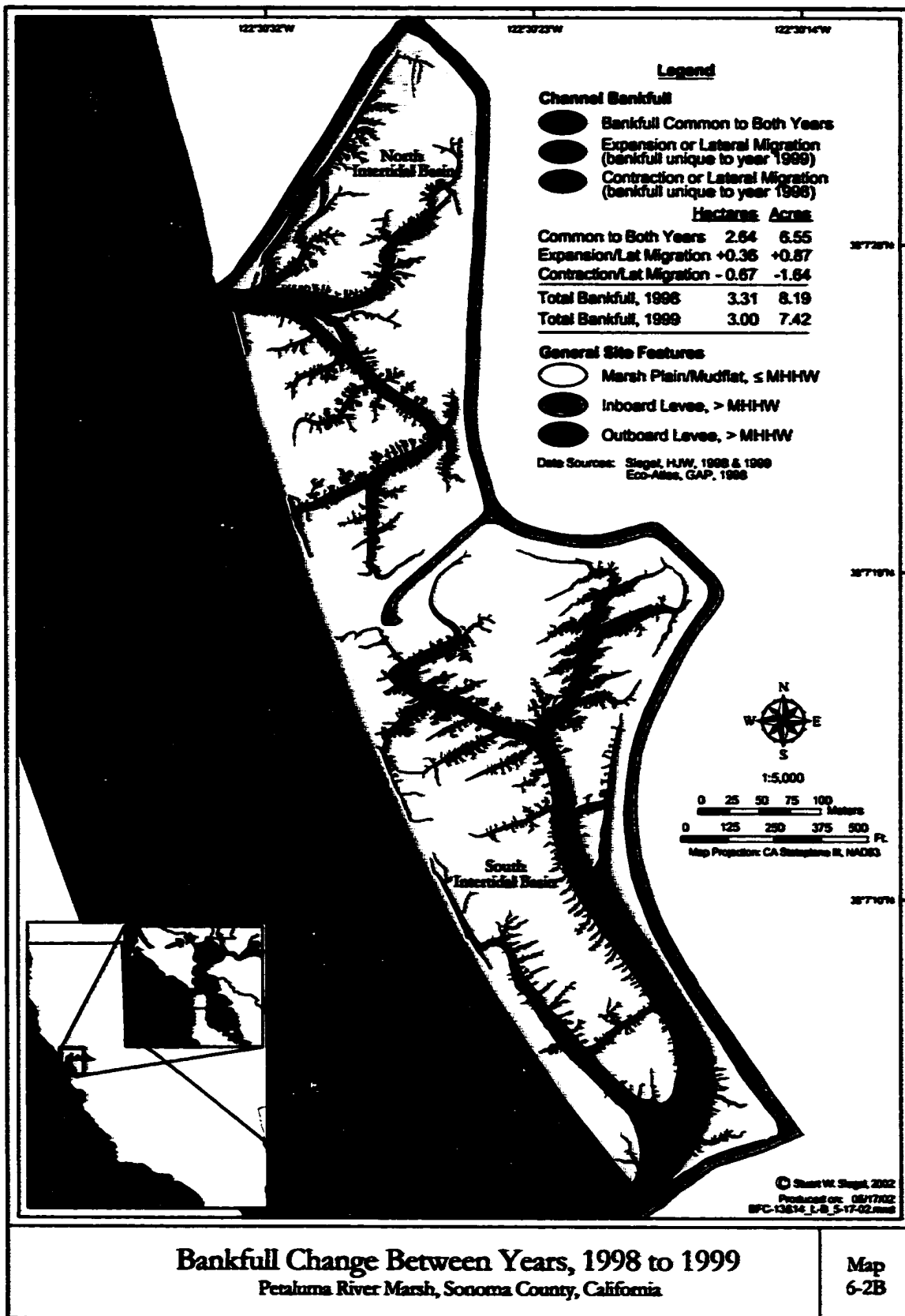
Primary Channel Bankfull with Initial Conditions, 1999
 Petaluma River Marsh, Sonoma County, California

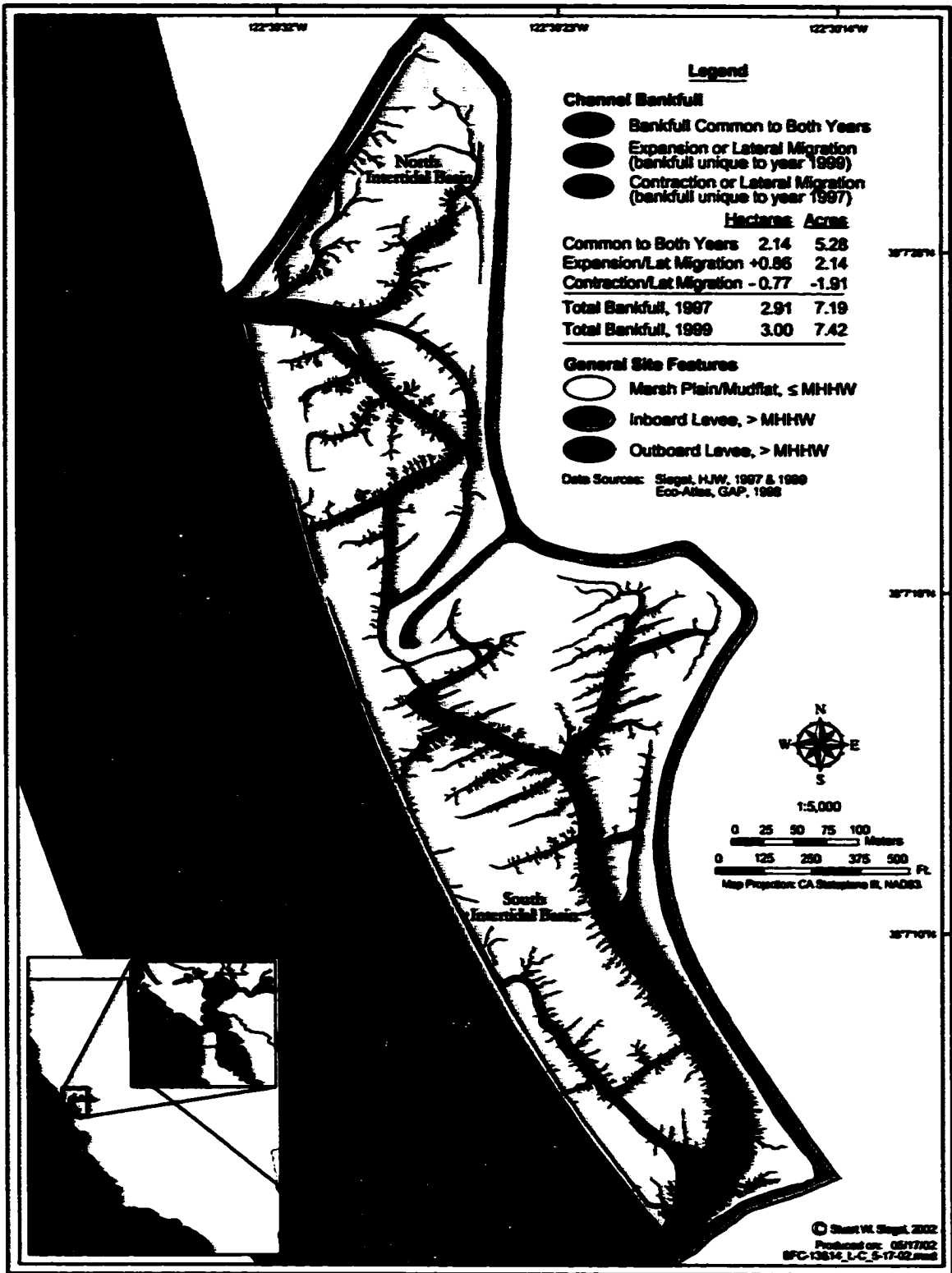
Map
 6-1C



Bankfull Change Between Years, 1997 to 1998
Petaluma River Marsh, Sonoma County, California

Map
6-2A





Bankfull Change Between Years, 1997 to 1999
Petaluma River Marsh, Sonoma County, California

Map
6-2C

6.1.1 Pilot Channel Planform Persistence in Primary Channels

Map 6-1 shows the pilot channels constructed as part of the restoration project. These channels were approximately 3m wide by 0.3m deep (10ft by 1ft) and were intended to help guide evolution of a channel network and to promote flooding and drainage throughout the site. The overlay of these pilot channels and the primary channel location in Map 6-1 clearly shows that the planform location of these pilot channels has persisted through to 1999 with only minor lateral migration. Subsequent aerial photography (in 2000 and 2001; see Maps 4-3B and 4-3C in Chapter 4) confirms the ongoing persistence of these channels. In other words, the largest channels on the site have adopted the antecedent channel morphology as defined by the pilot channels. In the North Basin, the headward extent of the pilot channel has filled in with sediment over time and become incorporated into the marsh plain. This infilling likely represents a reduction in discharge suggesting that, for the purpose of channel formation, the pilot channel may have been longer than necessary.

6.1.2 Failed Abandonment of Pilot Channel

One feature visible in Map 6-1 and very apparent in Map 6-2 is the early formation and subsequent loss of a major primary channel in the North Basin that might have led to abandonment of the pilot channel. In Maps 6-2A and 6-2B, this channel is visible as the large red channel, with the red color indicating its existence in March 1997 and its

loss by September 1998. Throughout this period, the channel bed was elevated above the underlying farm field (i.e., the channel existed wholly within newly deposited sediments). Its planform morphology appeared more naturalistic relative to the constructed pilot channel and aligned better with flood tidal flows through North Breach. However, Map 5-1 shows that some of the highest sediment accumulation in the North Basin occurred in and around this forming channel, essentially burying it. These results suggest that in some instances, adopting the antecedent channel morphology exerts a greater influence than natural formation even if the antecedent morphology does not define what natural processes may otherwise form (Pestrong 1965, Collins *et al.* 1987, Knighton *et al.* 1992, Allen 2000b).

6.1.3 Absence of Lateral Migration

Lateral migration would be evidenced by channel growth on one bank and channel retreat on the opposite bank and is one process that can lead to more sinuous channels commonly seen in old tidal marshes in the San Francisco Estuary. One of the most noticeable results evident from Map 6-2 showing channel bankfull change over time is that very little lateral migration occurred during the period monitored. This result applies to the pilot channels as well as the naturally formed channels. With the largest channels closest to each levee breach, some lateral migration occurred but at a small fraction of channel width. A hand full of the smaller channels exhibited migration up

to one channel width. These results support the concept that channels inherit antecedent morphology regardless of the origin of that morphology.

6.1.4 Ephemeral Borrow Ditches

Borrow ditches are levee-parallel features created by excavating soil for levee construction and maintenance. Borrow ditches are very common throughout the San Francisco Estuary because periodic levee maintenance is a routine activity necessary to maintain flood protection for inland areas. Depending on borrow ditch depths relative to the surrounding land, they can become significant yet unintended “pilot” channels, influencing patterns of tidal circulation and channel evolution.

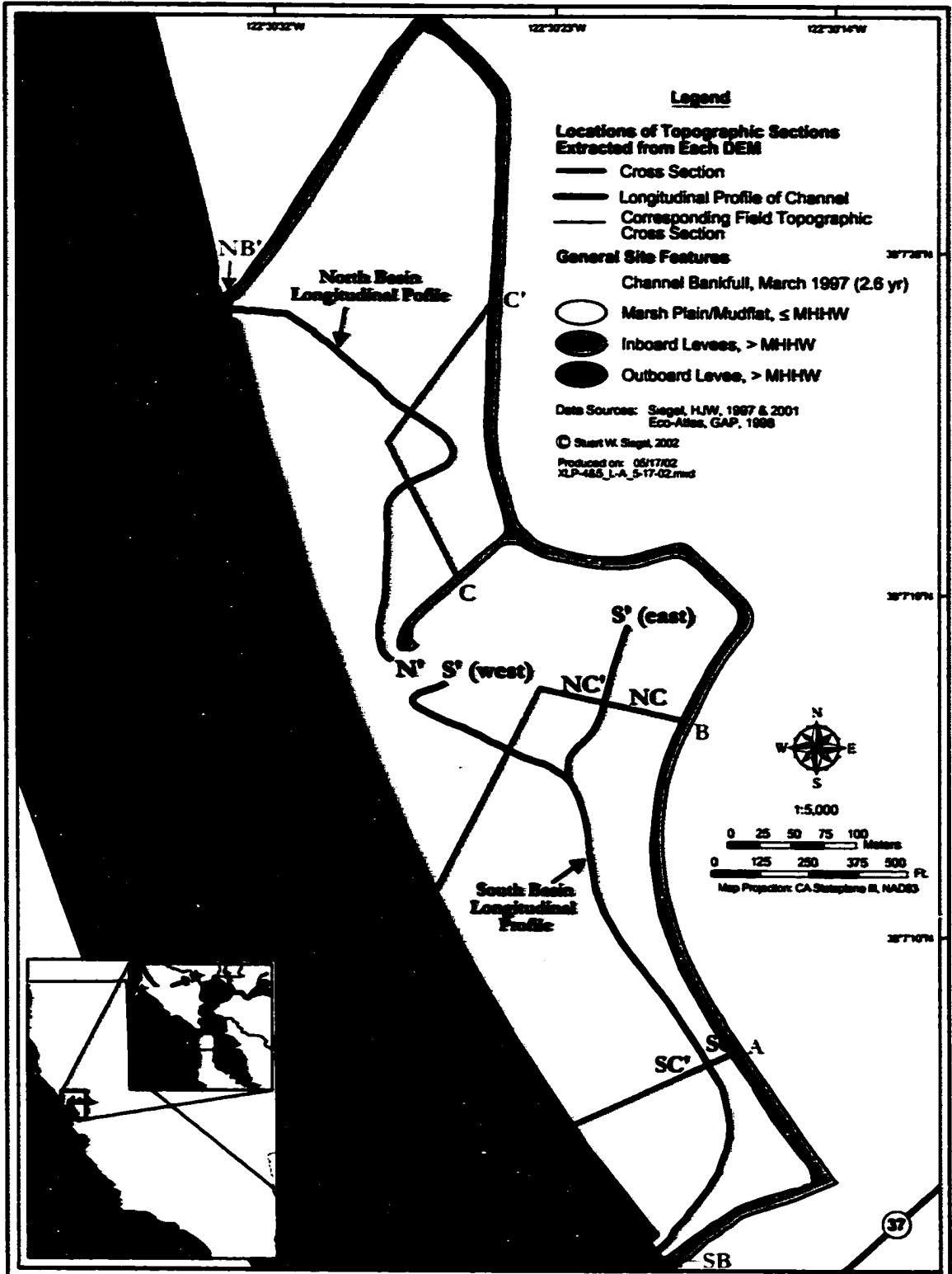
At the Petaluma River Marsh, borrow ditches from pre-restoration agricultural use of the site were located along the outboard levee and the northern levee (see Map 6-1A). Following restoration at this site, the borrow ditch along the outboard levee gradually filled in with sediment and by 1999 had largely disappeared (see Map 6-1C and Map 6-2C). The borrow ditch along the northern levee has remained in place, though it has decreased in size. This different outcome may be due to storm water discharge pumped into the channel by the adjacent farmer during extreme weather events.

6.2 Cross Sections

I collected field topographic surveys at two channel locations and each of the two levee breaches, I extracted cross section data from the DEMs for these same locations, and I extracted lengthy marsh plain – channel cross sections from the DEMs. Map 6-3 shows cross section locations for each year (same for all three years).

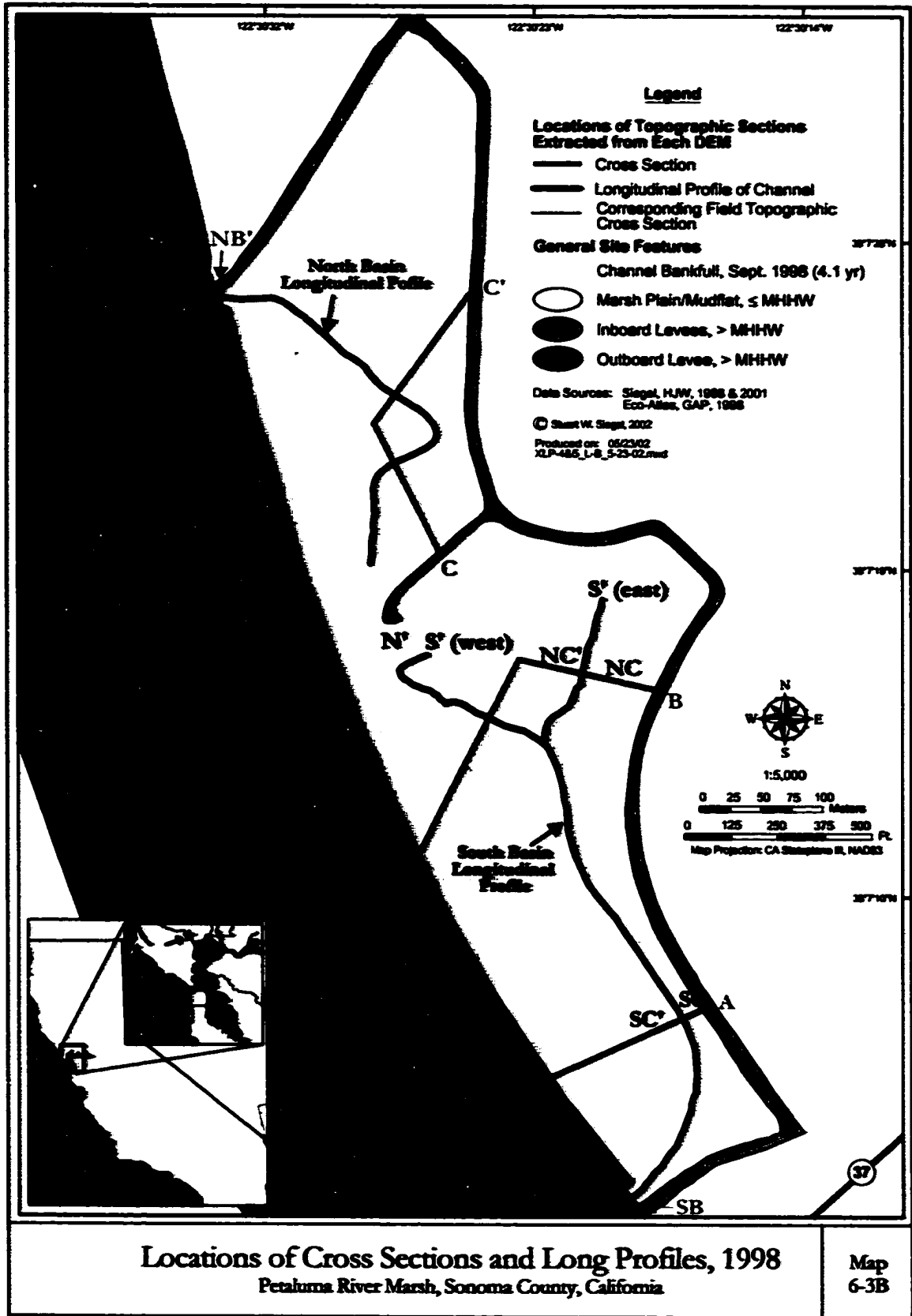
6.2.1 Levee Breaches

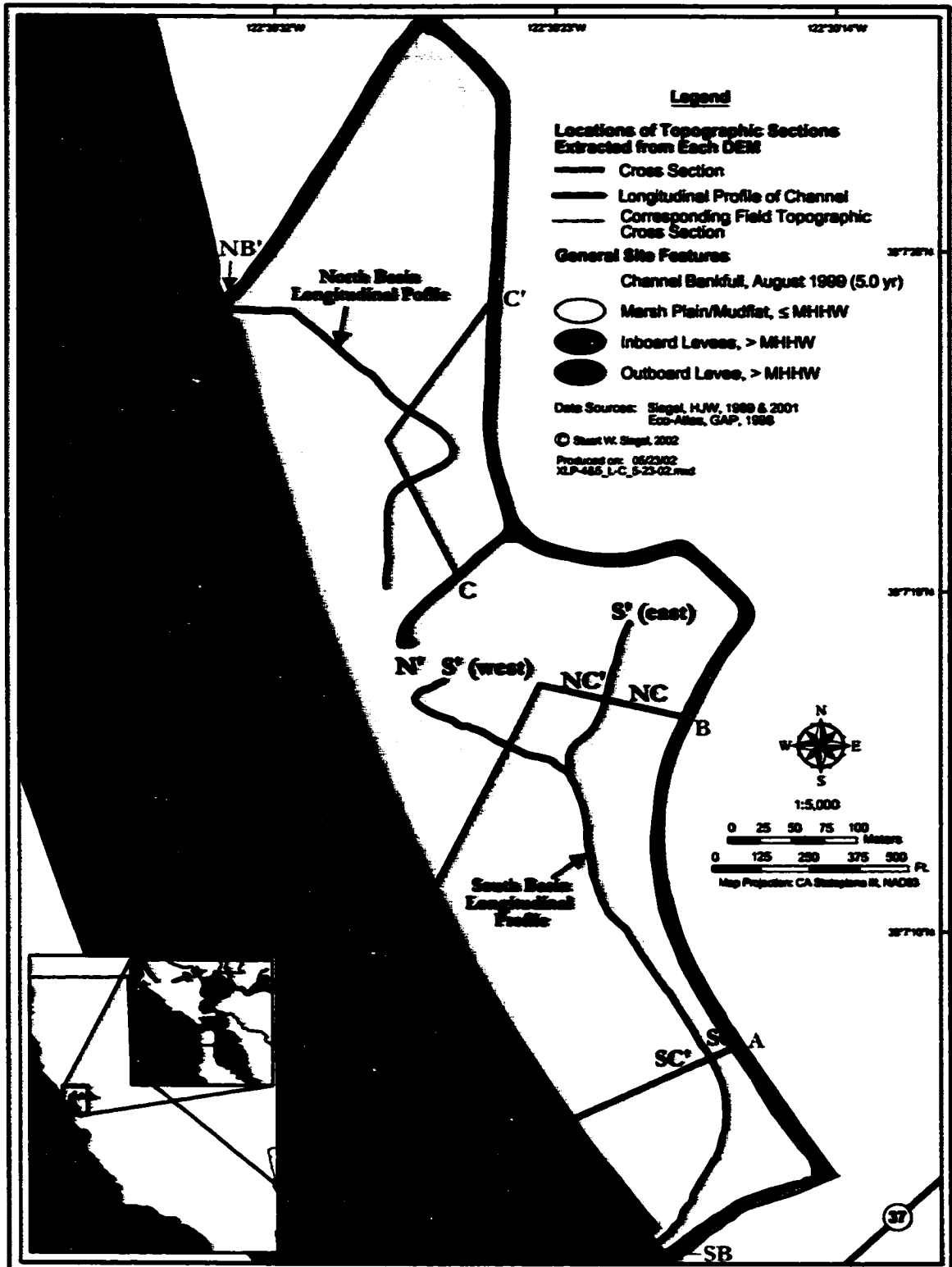
Figure 6-1 shows six levee breach cross sections from 1997 to 1999. Levee breach initial construction geometry was approximately 16 m (50 ft) wide at MHHW, invert elevations at MLLW or 1.9 m (6.2 ft) deep below MHHW, and U-shaped cross sections (Carl Wilcox, pers. comm.). Levee breach cross section widths at MHHW have remained stable over time.



Locations for Cross Sections and Long Profiles, 1997
Petaluma River Marsh, Sonoma County, California

Map
6-3A

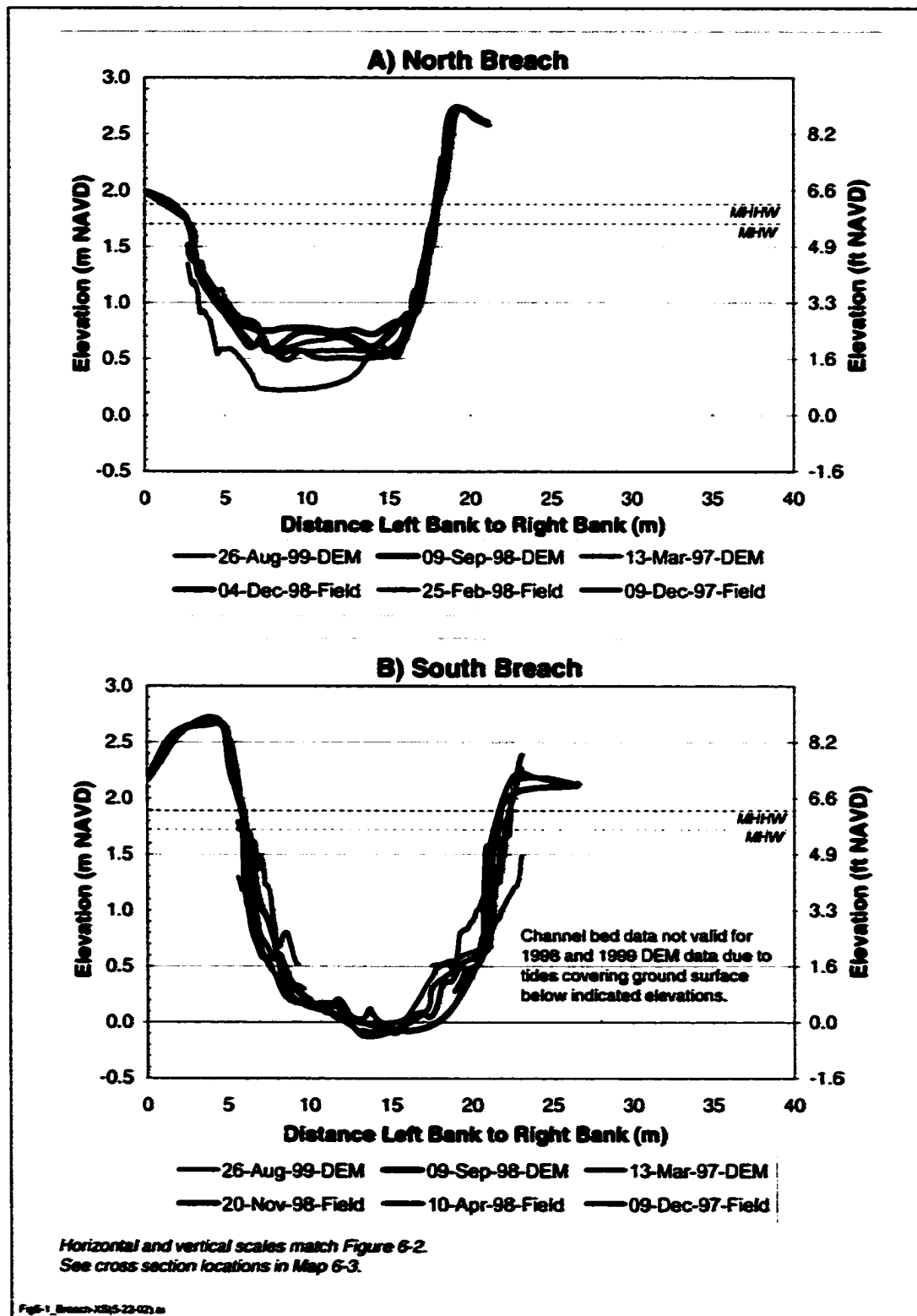




Locations of Cross Sections and Long Profiles, 1999
Petaluma River Marsh, Sonoma County, California

Map
6-3C

Figure 6-1. Levee Breach Cross Sections, Field and DEM



North Breach. The North Breach had already begun accumulating sediment at research initiation 2.6 years after restoration, which indicates the constructed cross sectional area was larger than necessary for the volume of the tidal prism exchanged through the breach. Figure 6-1A also suggests that the breach accreted through September 1998 then began to erode again as shown with the August 1999 data. These changes suggest that the cross sectional area continues to adjust in response to the evolving tidal prism, which responds to sediment accretion, consolidation, and desiccation, and the sediment load transported through the breach.

South Breach. The South Breach cross sectional geometry followed a different trajectory than the North Breach (Figure 6-1B). Throughout most of the research period, the South Breach did not accumulate sediment. During low tides, the original rough ground surface left behind by the construction equipment was plainly visible (see Photo 6-1).

Photo 6-1. South Breach at Low Tide, 22-Oct-1996



This view is to the west from the inboard levee at the southeast corner of the site, looking out across the accreted mudflat/marsh plain to the South Levee Breach at a lower tide. The Petaluma River is visible beyond the levee breach. Exposed soils underlying the old flood control levee are visible at either side of the breach.

Both the 1998 and 1999 DEM source aerial photography were flown at a low tide level that covered the ground surface at lower elevations, so the topography shown for the channel bed in Figure 6-1B below those elevations is not shown. Only following completion of the field research did the South Breach begin to accumulate sediment on the channel bed; visual estimates suggest about 0.5 m deposition during a site visit in fall 2001. These conditions suggest one of two possible conditions regarding South Breach cross sectional geometry: either it was large enough to accommodate tidal prism and sediment load, or it was undersized and thus subject to ongoing scour until considerable accretion reduced the tidal prism flowing through the breach with each

tide. Examination of channel planform geometry (Map 6-1) reveals that the channel widens a short distance inside the site from the South Breach, suggesting that the latter condition of undersized cross sectional geometry applied. Tidal flows through this breach, however, were insufficient to erode the breach bed and bank sediments, all of which were subjected to several decades of compaction while underlying a flood control levee.

6.2.2 Interior Pilot Channels

Figure 6-2 shows channel cross sections for two South Basin pilot channel locations. These plots are shown with horizontal and vertical scales matching that used in Figure 6-1 for the levee breaches, in order to allow comparison of channel geometry. Map 6-3 shows the cross section locations. The South Channel cross section extends from the enclosing levee, through the channel, and onto the adjacent marsh plain. Because the pilot channel at this location runs immediately adjacent to the levee, the channel does not have a geomorphically distinct bankfull position on the left bank. The zero position of that cross section is on the levee.

Photo 6-2 shows the South Basin pilot channel just bayward (south) of the cross section location, with a view southwest to South Levee Breach.

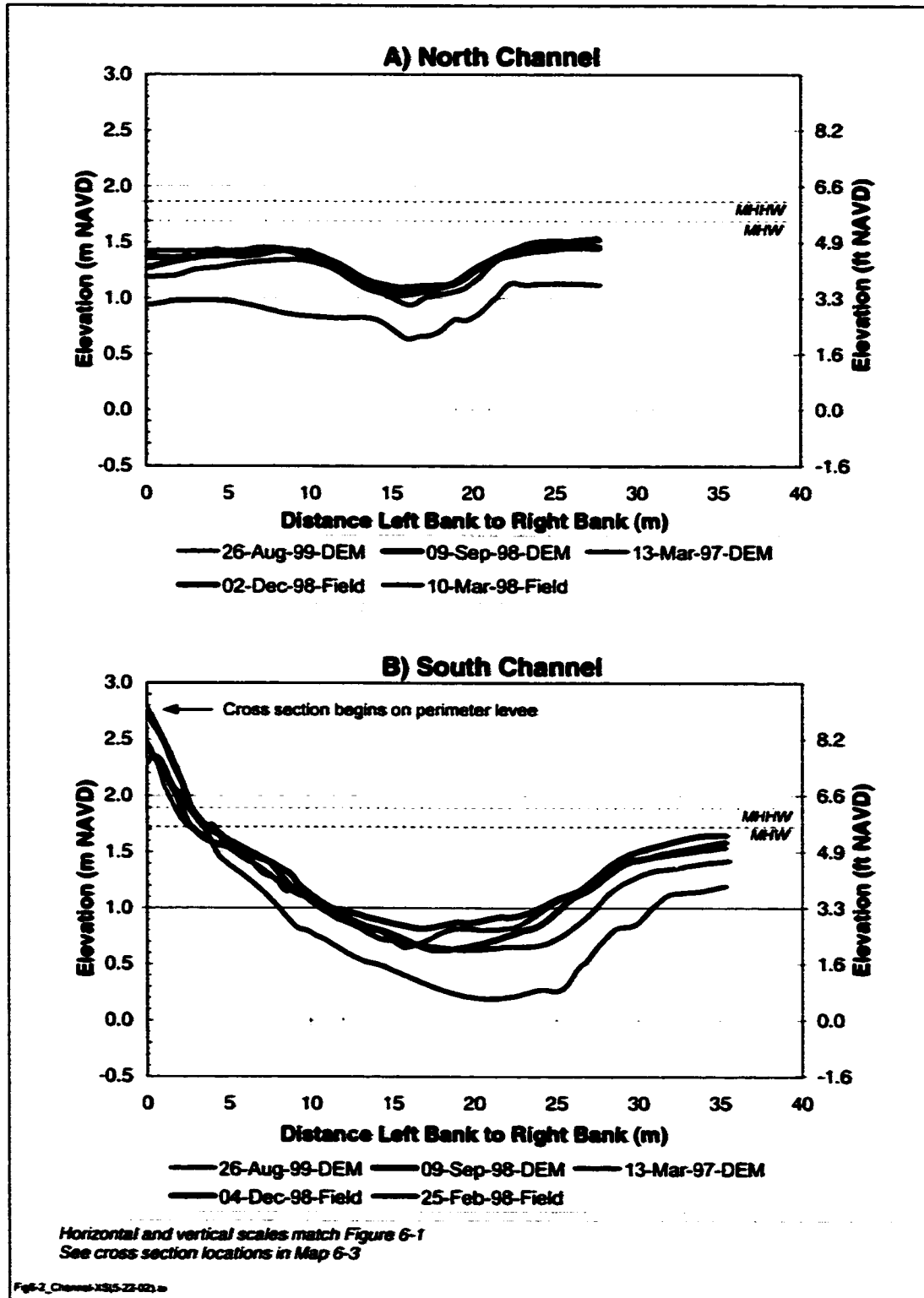
Photo 6-2. Interior Pilot Channel in South Basin, 22-Oct-1996



This view is to the southwest from the inboard levee at the southeast corner of the site, looking out across the accreted mudflat/marsh plain toward the South Levee Breach at a lower tide. The thalweg of the large channel is visible on the right. This photo illustrates the shallow slopes of channel banks at this site, which at the time of this photograph was still a mudflat.

These data reveal two important channel temporal evolution attributes. First, lateral migration has been a minor process in both locations while the channels have adjusted upward vertically. The South Channel centerline has shifted a few meters toward left bank in conjunction with a slightly smaller magnitude narrowing of channel width. Map 6-1, which shows channel planform morphologic change, supports the conclusion that minimal lateral migration has occurred. Further, channel lateral migration in restored wetlands is often of concern if it results in erosion (Solano County and USACE 1996). In the situation here, the channel has shifted slightly as it rises vertically but is not associated with bank erosion.

Figure 6-2. South Basin Interior Pilot Channel Cross Sections, Field and DEM



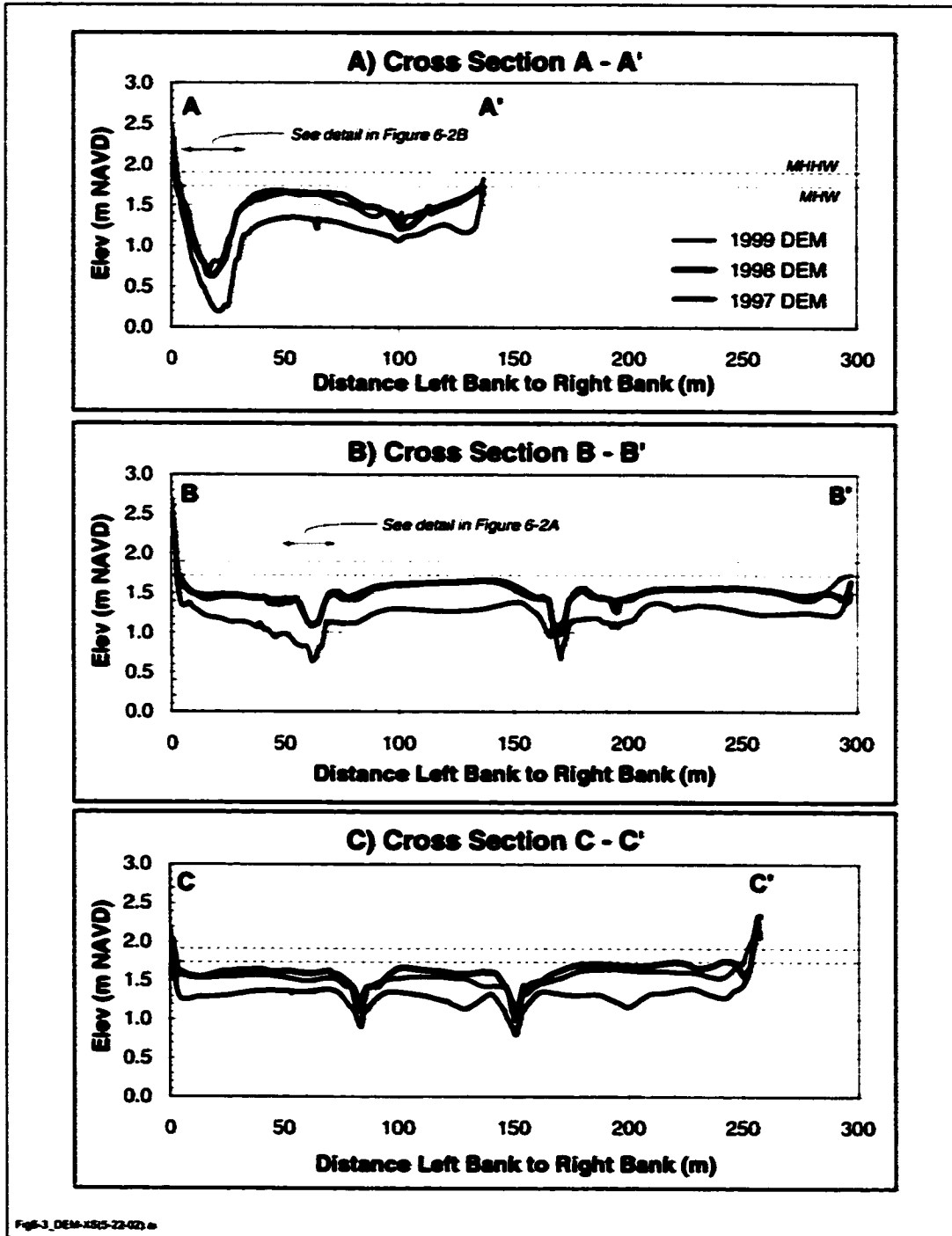
Second, as the site filled with sediment, the channel bankfull cross sectional area (the area of the channel relative to the adjacent mudflat/evolving marsh plain) declined by a small amount; in other words, the entire channel geometry essentially rose in elevation as the site accreted. This same phenomenon can be observed in the DEM point topographic data for the entire site shown in Figure 5-2 in Chapter 5. That figure shows that the marsh plain median elevation rose about 0.3m between March 1997 and August 1999 whereas the channels rose about 0.4m. This differential accretion suggests that as the site filled with sediment, a slightly smaller channel cross sectional area was sufficient to convey the evolving tidal prism and sediment load. In contrast at the South Channel location (Figure 6-2B), elevations reached their maximum in late 1998 and by August 1999 had dropped 0.1 to 0.2 m (0.3 to 0.6 ft) in the channel and adjacent marsh plain. The marsh plain elevation in December 1998 had nearly reached MHW when this reversal began.

6.2.3 Marsh Plain

Figure 6-3 shows the three DEM-derived marsh plain cross sections for the locations shown in Map 6-3. These cross sections show the topographic increases across the entire marsh plain and channels over time, the general retention of channels in cross sectional area and horizontal position over time, and the general increase in channel definition with time. At these cross sections, elevation increases ranged from about 0.2 to 0.4 m (0.6 to 1.2 ft) from March 1997 to August 1999. These cross sections also

show that in some of locations where the marsh plain had accreted close to MHW by September 1998, elevations subsequently decreased. This result suggests that as the marsh plain approaches some threshold elevation, consolidation and desiccation processes that contribute toward a decline in ground surface elevation may become more important relative to the sediment influx that contributes toward accretion. Figure 5-1 in Chapter 5 shows that over the study period, peak net sediment influx per tide declined somewhat but remained a net influx.

Figure 6-3. Marsh Plain Cross Sections, from DEM

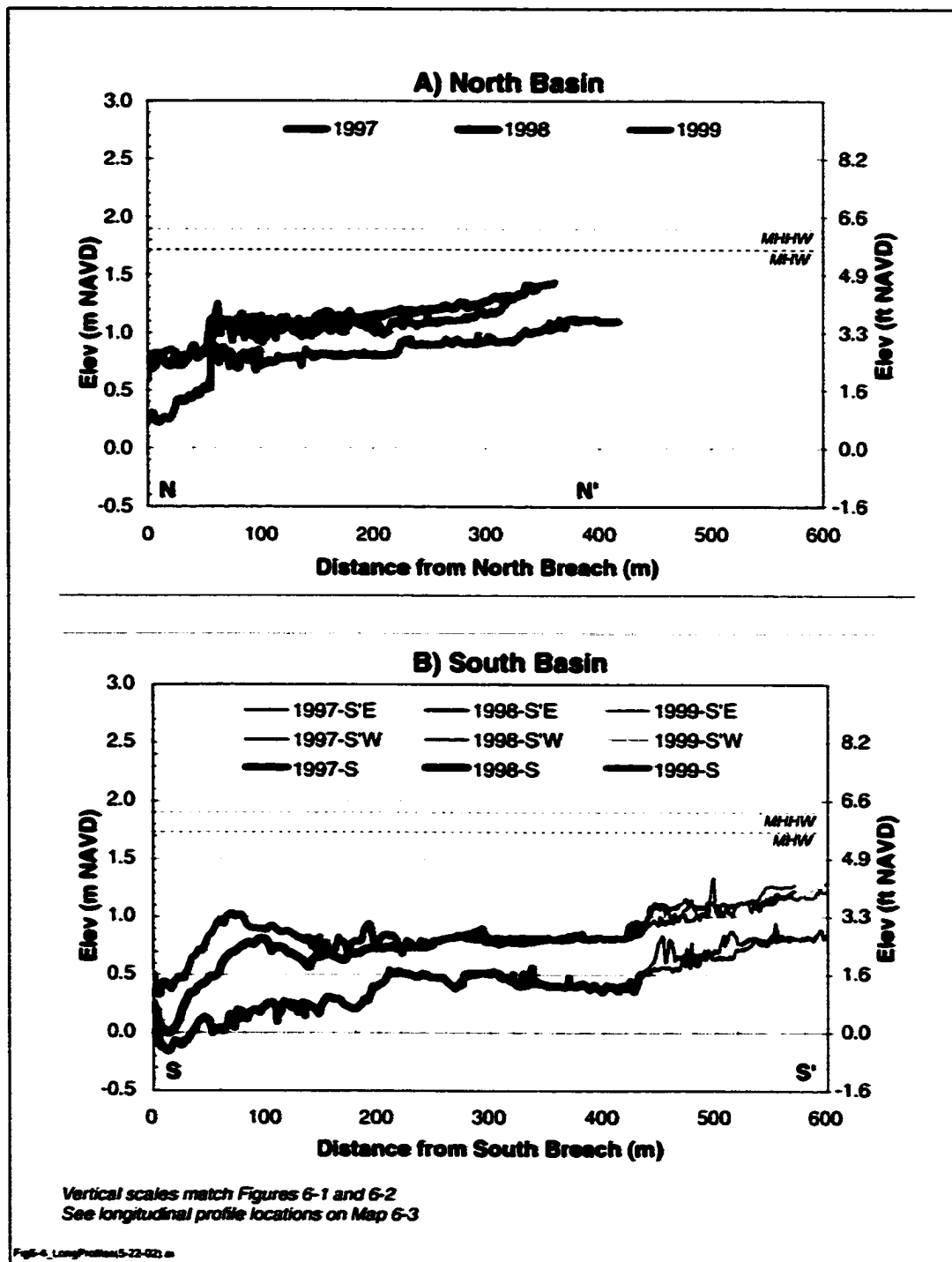


6.3 Long Profile Evolution of Pilot Channels

Figure 6-4 shows the longitudinal profiles for the pilot channels along the locations shown in Map 6-3. Longitudinal profiles show the channel bed topography beginning at each levee breach and traversing the centerline path upgradient (headward) to the upper reaches of the marsh. Figure 6-3a shows the North Basin, a single pilot channel, and Figure 6-4b shows the South Basin, in which the pilot channel splits into two separate channels about 420 m headward of the levee breach. For the South Basin, Figure 6-4b denotes these two separate upper channel reaches by the qualifiers “E” (for east) and “W” (for west). The topographic heights of local MHW and MHHW are also included for reference.

The high-frequency, low amplitude “roughness” of these profiles, in contrast to a smooth line, represents the criss-crossing of the channel thalweg to either side of the channel centerline. The thalweg is generally quite sinuous within a much lower-sinuosity pilot channel (see Map 4-5 in Chapter 4). Some of the high-frequency profile roughness may be due to the DEM generation process (see methods in Chapter 4).

Figure 6-4. Longitudinal Profiles for Pilot Channels, from DEM



6.3.1 North Basin

The North Basin pilot channel longitudinal profile shows a number of features. First, the channel bed overall rises headward of the levee breach for all three years, as would be expected traversing from bayward to headward channel extent. Second, there are some relatively flat or very low-gradient regions. These areas represent flat expanses of channel and may correspond to the tri-modal peaks in the channel elevation distribution evident in Figure 5-2 in Chapter 5. Third, sinks or depressions exist along the channel suggesting that very low-flow drainage (i.e., the end of the ebb tides) occurs only via the sinuous channel thalweg rather than across the full width of the channel. Fourth, the channel bed increases about 0.4m to 0.5m from March 1997 to August 1999 then decreases along much of its length by up to 0.2m from September 1998 to August 1999. This trend may reflect an initial decrease of the tidal prism as the site continued to accrete (see Map 5-1A in Chapter 5) followed by an increase in the tidal prism as site elevations lowered through consolidation and desiccation. Fifth, a knick point or sharp change in elevation remained throughout the monitoring period at a location approximately 60 m headward of the levee breach. This location coincides with the junction of several smaller channels forming the main channel draining out the North Breach. Sixth, the pilot channel retreated in length at its headward end from a total length in 1997 of 417 m to a total length of 360 m in 1998 and 1999. This retreat presumably coincides with an overall decrease in tidal prism as the North Basin accreted combined with the relatively high sediment load in the water column. Lastly, the elevations at the breach and headward end of the pilot channel

were, respectively, 0.2m and 1.1m for 1997, 0.8m and 1.4m for 1998, and 0.6m to 1.4m for 1999. At the breach end, the channel bed thus rose 0.6m from March 1997 to September 1998 then dropped 0.2m from September 1998 and August 1999. All elevations from the DEM are $\pm 0.05\text{m}$.

6.3.2 South Basin

The South Basin pilot channel longitudinal profile (Figure 6-4B) shows a number of features, many of which it shares with the North Basin longitudinal profile. First, the channel bed overall rises headward of the levee breach for all three years. In contrast to the North Basin, however, the longitudinal patterns are more varied especially in later DEMs, showing a large rise then drop at about 95m in 1998 and at about 65m in 1999. Second, there are some relatively flat or very low-gradient regions, with the reach from about 200–400m in March 1997 and 100–400m in September 1998 and August 1999 being essentially flat (zero slope). Third, sinks or depressions exist along the channel suggesting that very low-flow (i.e., late ebb tides) drainage occurs only via the sinuous channel thalweg. Field observations confirm that the pilot channel drains fully at low tide. Fourth, the channel bed elevations show continued elevation increases from 1997 to 1998 to 1999, in contrast to North Basin. Fifth, the magnitudes of elevation increases are greater than in the North Basin, ranging from about 0.2m to 1m from March 1997 to August 1999. Sixth, within each year, the two upper branches

of the pilot channel have similar but not identical centerline elevations and a small knickpoint, about 0.2-0.3m, remains at the channel split.

6.4 Channel Network Evolution from Initial Conditions

The channel network at Petaluma River Marsh can be examined in two manners: (1) the complete network that includes all primary (larger) and secondary (smaller) channels, or (2) as the primary channels only. Secondary channels are the small (under 1m wide and a few meters in length) “rill” channels that typically drain normal to the larger primary channels and in most instances are first and second order channels.

The purpose of separating out the primary and secondary channels is that the primary channels represent a vast majority of channel volume and thus convey a bulk of the water, sediment, nutrients, and organisms into, through, and out of the site. Further, such a separation allows one to examine the effects of scale in examining channel networks at tidal marshes, an importance tool because channel networks are often evaluated from aerial photography and thus the scale of photography can influence analytical results.

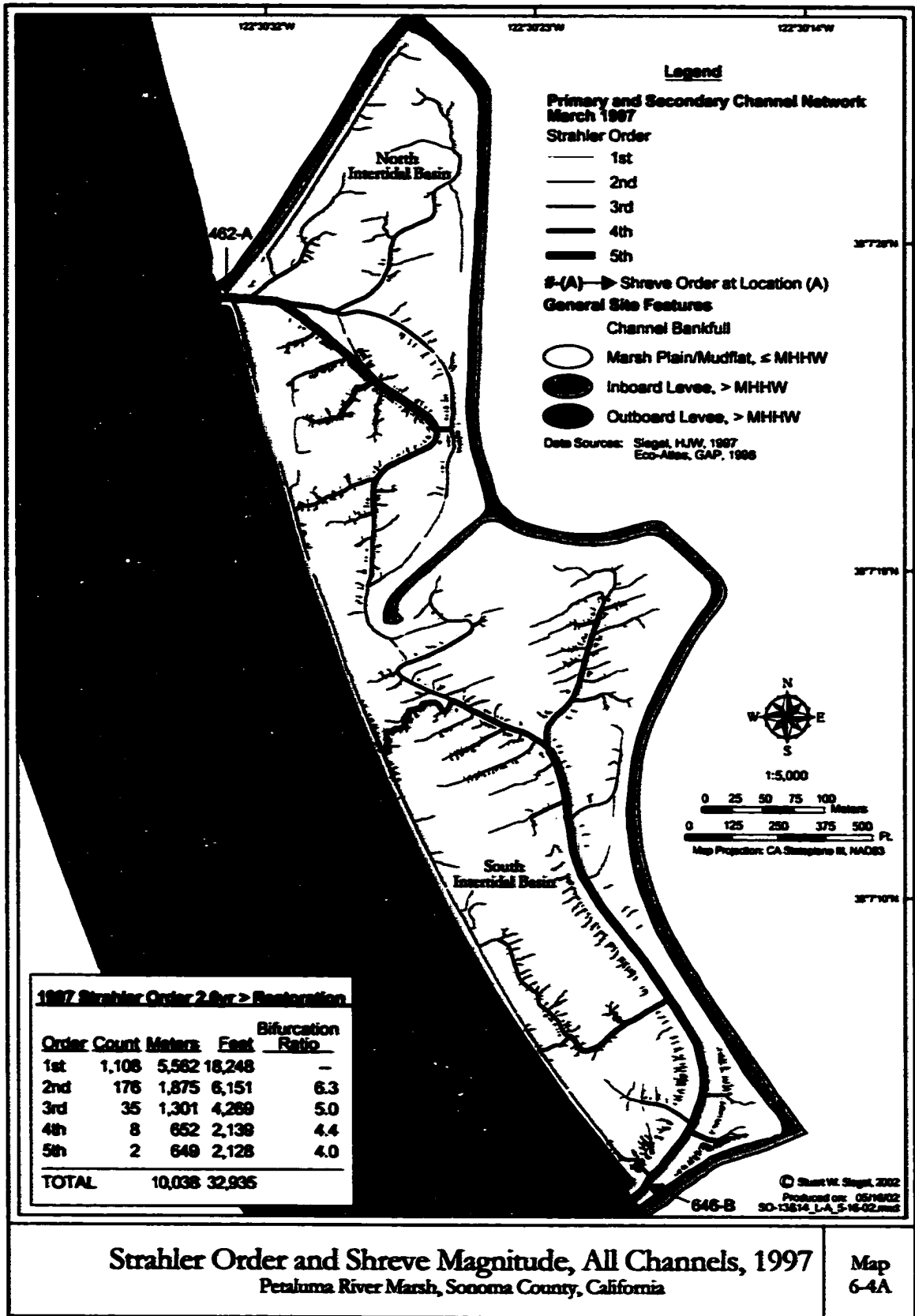
The channel network analysis quantifies the channel geomorphology at the site, which provides the opportunity for comparison to other marshes and data for designing similar tidal marsh restoration efforts. Performance of the following analyses does not

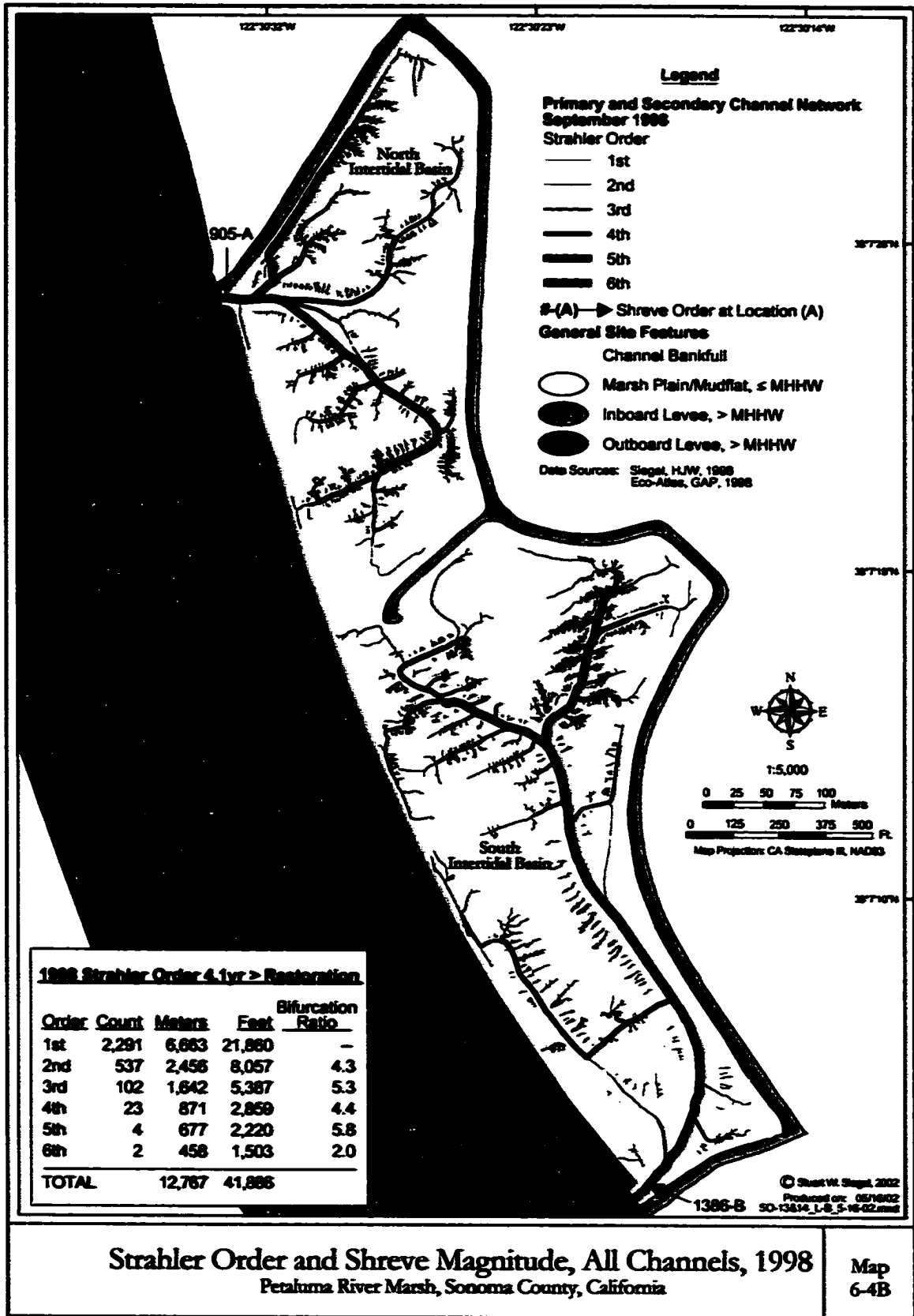
mean that each provides a useful indicator of channel network character; instead, some of these analyses have limited utility yet are still used by restoration practitioners. The appropriateness of that application warrants examination.

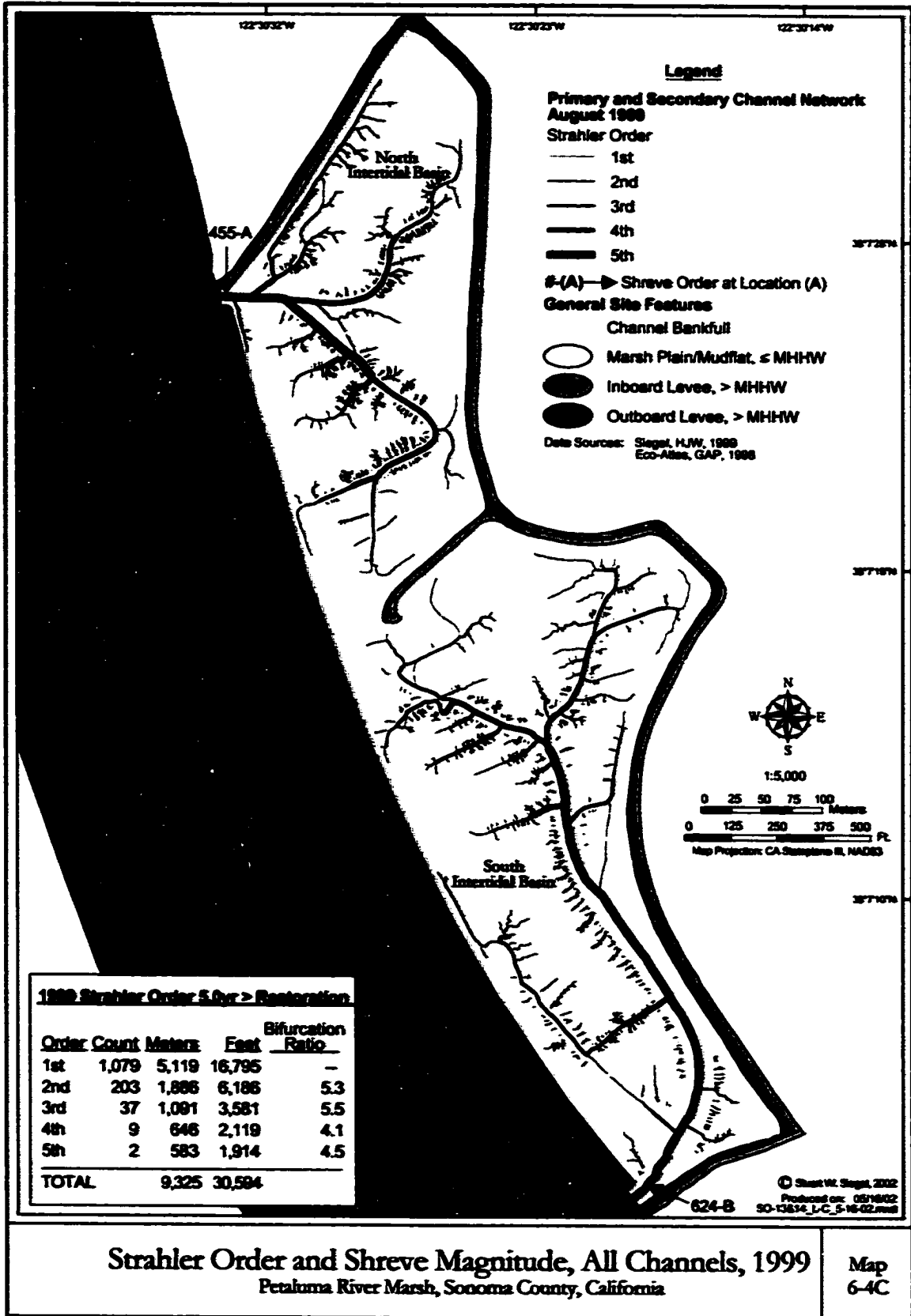
The network analysis consists of several attributes:

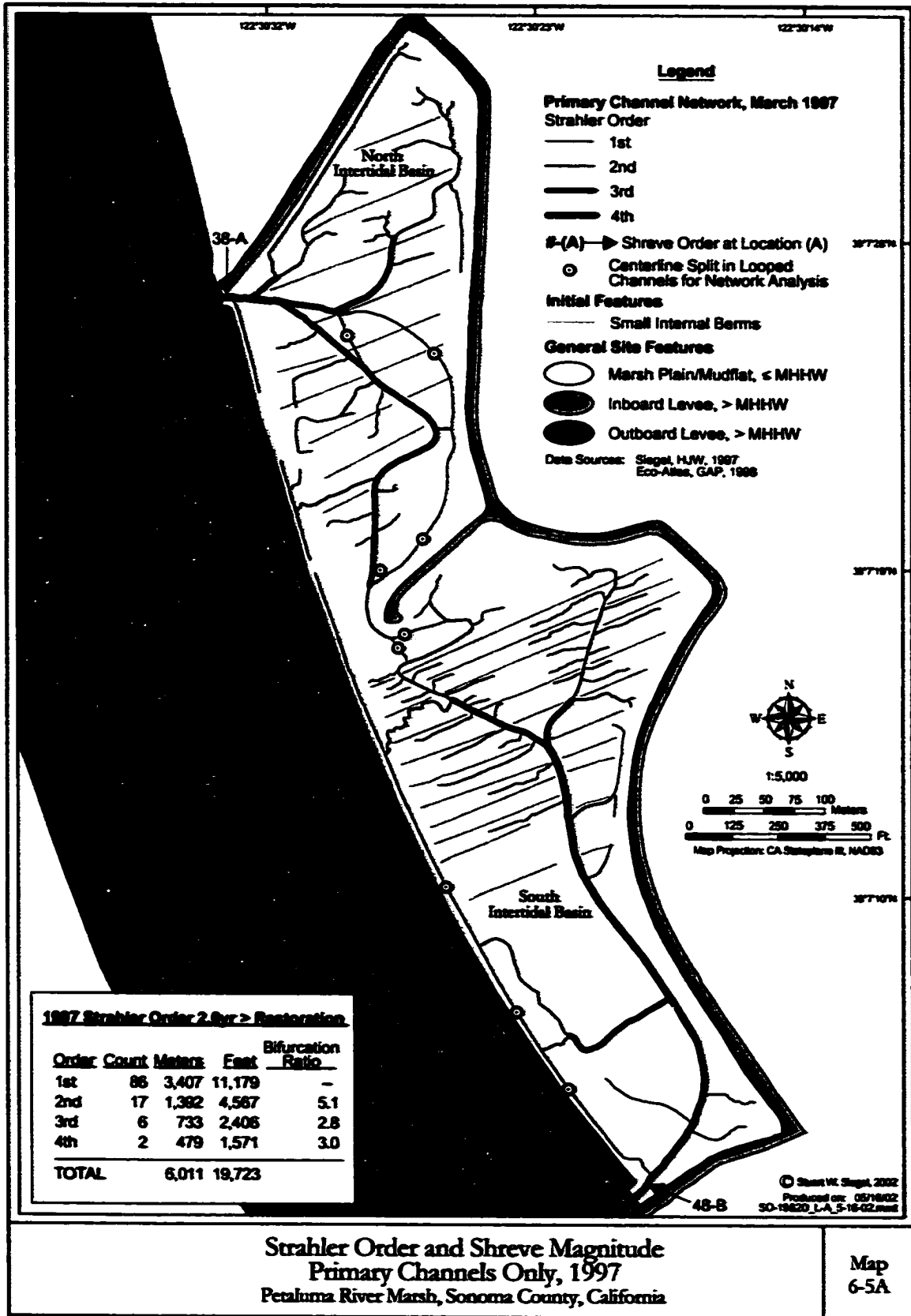
- **Section 6.4.1: Shreve magnitude**
- **Section 6.4.2: Strahler order**
- **Section 6.4.3: Bifurcation ratio and sinuosity**
- **Section 6.4.4: Channel centerline length**
- **Section 6.4.5: Channel surface area**
- **Section 6.4.6: Channel areal and linear density**

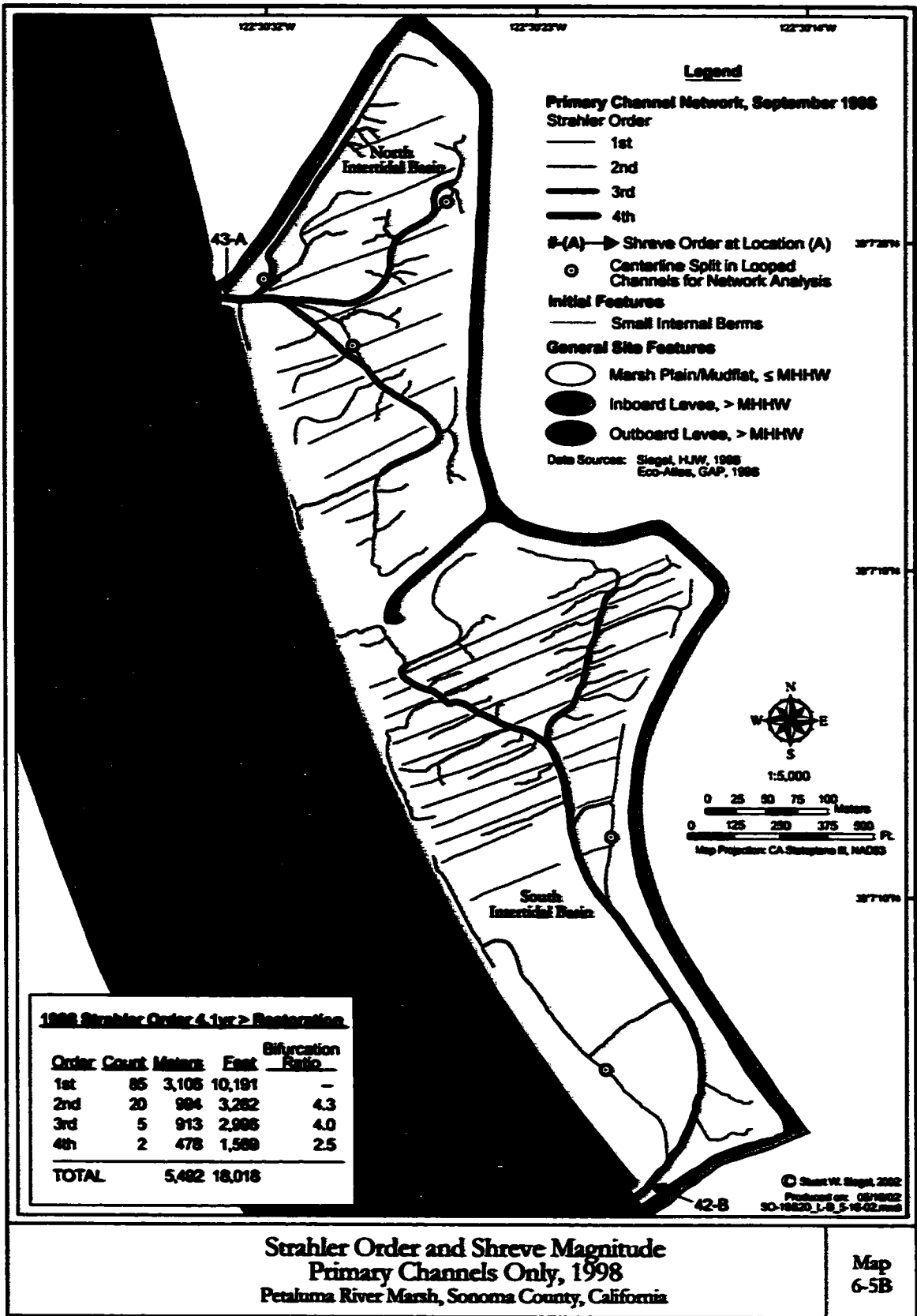
Each of these attributes is quantified in Table 6-1 and Strahler order and Shreve magnitude are shown spatially in Map 6-4 for the full network and Map 6-5 for the primary channel-only network. Table 6-2 compares many of these values to that reported by Allen (2000b) from several locations globally.











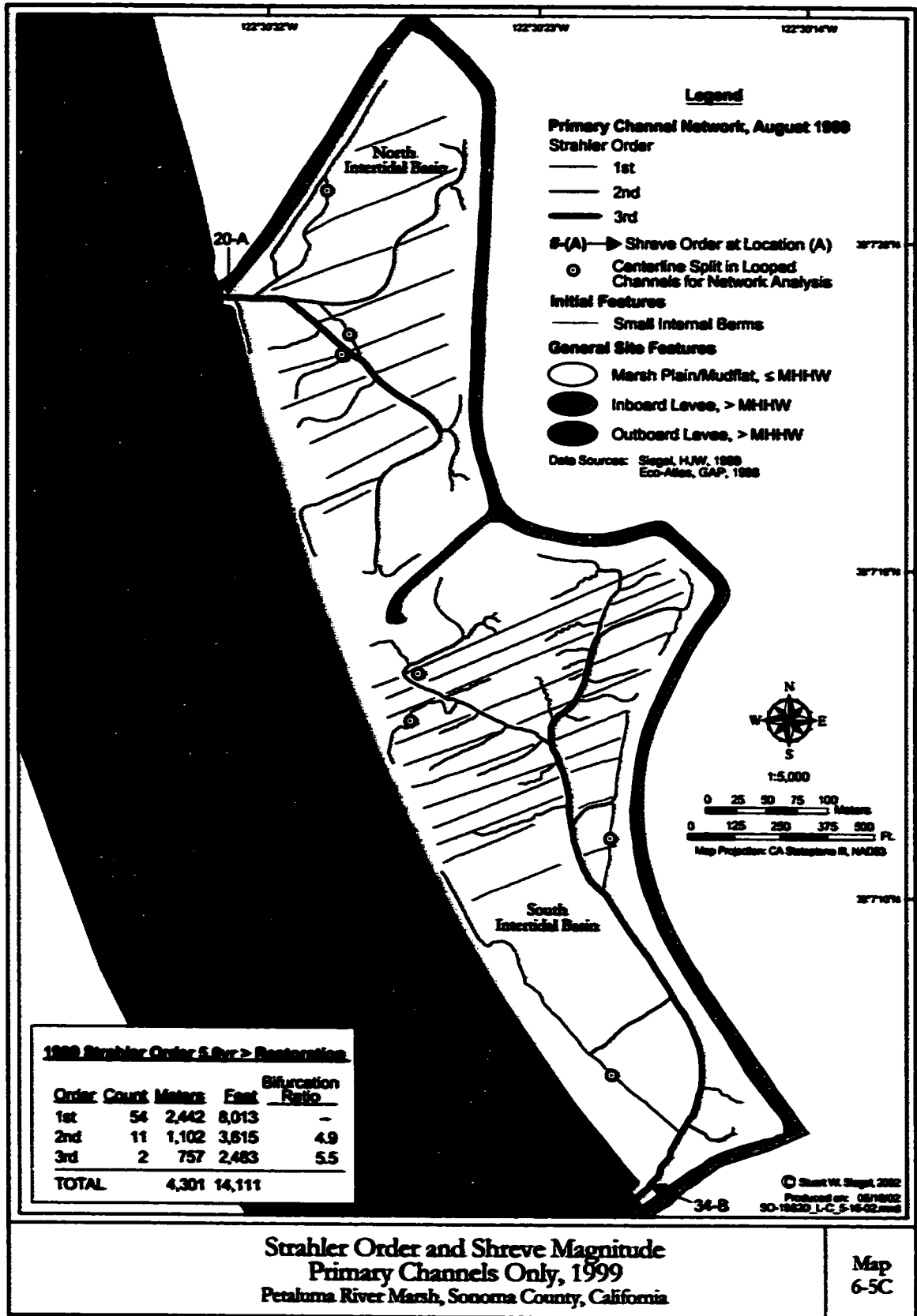


Table 6-1. Channel Network Geomorphic Attributes

Attribute	Attribute Value By Network Basis, Year, and Basin ^{1,2,3,4}											
	A) Channel Network Comprised of Primary and Secondary Channels						B) Channel Network Comprised of Primary Channels Only					
	1997		1999		1999		1997		1999		1999	
	SB	NB	Total	SB	NB	Total	SB	NB	Total	SB	NB	Total
Strahler order⁵ (# channels)												
1	646	462	1108	1396	905	2301	624	455	1079	48	36	86
2	99	77	176	332	205	537	110	93	203	7	10	17
3	20	15	35	66	36	102	18	19	37	3	3	6
4	4	4	8	12	11	23	4	5	9	1	1	2
5	1	1	2	2	2	4	1	1	2			
6				1	1	2						
Shreve magnitude (# 1st order)	646	462	1108	1396	905	2301	624	455	1079	48	36	86
Bifurcation ratio⁶ (ratio)												
1st to 2nd order	6.63	6.00	6.30	4.17	4.41	4.27	6.67	4.89	5.32	6.66	3.80	5.06
2nd to 3rd order	4.86	5.13	5.03	5.03	5.09	5.26	6.11	4.89	5.49	2.33	3.33	2.83
3rd to 4th order	5.00	3.76	4.38	5.50	3.27	4.43	4.50	3.80	4.11	3.00	3.00	3.00
4th to 5th order	4.00	4.00	4.00	6.00	5.50	5.75	4.00	5.00	4.50			
5th to 6th order				2.00	2.00	2.00						
Average	6.12	4.72	4.92	5.18	4.72	4.93	5.07	4.65	4.95	4.06	3.38	3.63
Centrifuge length⁷ (m ± 2σ)												
1st order	3,650	2,011	5,662	2,734	3,929	6,663	2,964	2,165	5,119	2,131	1,275	3,405
2nd order	1,046	828	1,875	1,575	990	2,466	1,034	861	1,895	667	735	1,392
3rd order	599	702	1,301	924	717	1,642	688	403	1,091	241	492	733
4th order	450	201	652	514	357	871	280	365	646	433	46	479
5th order	432	216	649	244	432	677	432	161	593			
6th order				433	25	458						
Total:	6,079	3,959	10,037	6,425	6,341	12,766	5,399	3,935	9,325	3,461	2,548	6,009
Percent total:	61%	39%	100%	50%	50%	100%	59%	42%	100%	34%	25%	60%
Centrifuge length⁷ (ft ± 80)												
1st order	11,649	6,598	18,248	8,970	12,890	21,860	9,682	7,103	16,785	6,991	4,182	11,173
2nd order	3,433	2,718	6,151	5,169	2,888	8,057	3,393	2,794	6,186	2,155	2,411	4,566
3rd order	1,966	2,302	4,268	3,033	2,354	5,387	2,259	1,322	3,581	790	1,614	2,404
4th order	1,478	660	2,138	1,688	1,171	2,859	920	1,199	2,119	1,419	162	1,571
5th order	1,419	708	2,128	801	1,419	2,220	1,419	495	1,914			
6th order				1,421	82	1,503						
Total:	19,945	12,968	32,933	21,082	20,604	41,686	17,682	12,912	30,594	11,355	8,359	19,714
										10,503	7,515	18,018
										6,935	6,185	14,129

Table 6-1. Channel Network Geomorphic Attributes, continued

Attribute	Attribute Value By Network Basis, Year, and Basin 1,2,3,4											
	A) Channel Network Comprised of Primary and Secondary Channels						B) Channel Network Comprised of Primary Channels Only					
	1997		1998		1999		1997		1998		1999	
	SB	NB	Total	SB	NB	Total	SB	NB	Total	SB	NB	Total
Area (hectare, ± 0.01)												
Primary channels	1.73	0.99	2.72	2.12	0.84	2.97	1.94	0.79	2.73	2.12	0.84	2.97
Secondary channels	0.12	0.07	0.19	0.22	0.12	0.35	0.14	0.13	0.27	0.12	0.13	0.25
Intertidal basin	6.37	5.89	14.26	7.87	5.98	13.85	8.14	6.03	14.18	6.10	6.11	14.20
Total area <MHHW, hect.	10.22	6.95	17.17	10.22	6.95	17.17	10.22	6.95	17.17	10.22	6.95	17.17
Area (acre, ± 0.02)												
Primary channels	4.27	2.46	6.72	5.24	2.06	7.33	4.80	1.96	6.76	5.24	2.06	7.33
Secondary channels	0.50	0.16	0.46	0.55	0.31	0.86	0.34	0.32	0.66	0.34	0.32	0.66
Intertidal basin	20.88	14.55	35.23	19.45	14.78	34.23	20.10	14.90	35.00	20.01	15.09	35.10
Total area <MHHW, ac.	25.25	17.17	42.42	25.25	17.17	42.42	25.25	17.17	42.43	25.25	17.17	42.43
Area ratio ⁵ (ratio)												
Primary/secondary	14.2	15.1	14.5	9.5	6.8	8.5	13.9	6.2	10.2			
Channel Density												
1) Length/Area (Linear)												
a) m/m ² (± 2.0)	79.0	75.6	77.6	83.5	121.1	98.7	70.0	75.2	72.1	45.0	43.8	42.5
b) km/km ² (± 1.6)	59.5	57.0	58.5	62.9	91.2	74.4	52.7	56.6	54.3	33.9	33.0	32.0
2) Area/Area (%) (± 0.3)	18.1%	15.3%	16.9%	23.0%	13.9%	19.3%	20.4%	13.2%	17.5%	16.9%	14.3%	15.6%

Notes

1. Three years of data summarized in this table: March 1997, September 1998, August 1999
2. Restoration site comprised of two basins, South Basin and North Basin, separated by levee to PG&E tower (see Map4-1).
3. Primary channels are the larger channels; secondary channels are the smallest channels tributary to the large channels.
4. All data extracted from GIS coverage developed for the site.
5. Strahler order scale dependent; data obtained from orthorectified 1:2400 aerial photography scanned at 1,200 dpi
6. Bifurcation ratio = # of channels of order X / # of channels of next higher order
7. Channel centerline lengths include pilot channels, borrow ditches, and naturally formed channels
8. Area ratio = primary channel area/secondary channel area

Table 6-2. Channel Network Attributes Compared to Other Marshes

Source¹	Bifurcation Ratio	Length Ratio	Linear Drainage Density (km km⁻²)
Ragotzkie (1959) ²			29.5
Pestrong (1965) ²	3.22 - 5.45 (avg. 3.98)	1.98 - 5.91 (avg. 3.07)	41.6 - 149 (avg. 87.6)
Pethick (1980) ²	4.35	2.20	33.8
Woldenberg (1972) ³	3.03 - 4.56 (avg. 3.84)		
Knighton <i>et al.</i> (1992) ⁴	3.97 - 4.35 (avg. 4.21)	1.68 - 2.05 (avg. 1.80)	
Steel and Pye (1997) ²	3.25 - 4.42 (avg. 3.95)		15 - 128 (avg. 58.3)
This study⁵:			
a) full network	2.00 - 6.53 (avg. 4.69)	0.56 - 17.3 (avg. 2.50)	52.7 - 91.2 (avg. 63.3)
b) primary channels only	2.00 - 6.86 (avg. 4.05)	0.56 - 13.7 (avg. 3.21)	22.8 - 36.7 (avg. 30.7)

Notes:

1. Table adapted from Allen (2000b: Table 1)
2. Salt marshes
3. Salt marshes and networks draining linked marshes and mudflats.
4. Tidal networks rapidly invading vegetated coastal plain.
5. Data from Table 6-1.

6.4.1 Shreve Magnitude

Shreve magnitude is a network analytical method that provides a count of the number of first order channels in a watershed (Shreve 1967). Its results are clearly scale-dependent in that scale of analysis determines the number of first order channels

identified. Shreve values can be determined for any particular point in the watershed, with the number increasing downstream (bayward). At this research site, the simplest Shreve magnitude values to compare are at each of the two levee breaches. For each breach location, Shreve magnitude results are tabulated in Table 6-1 and shown graphically in Map 6-4 (full network) and Map 6-5 (primary channels only).

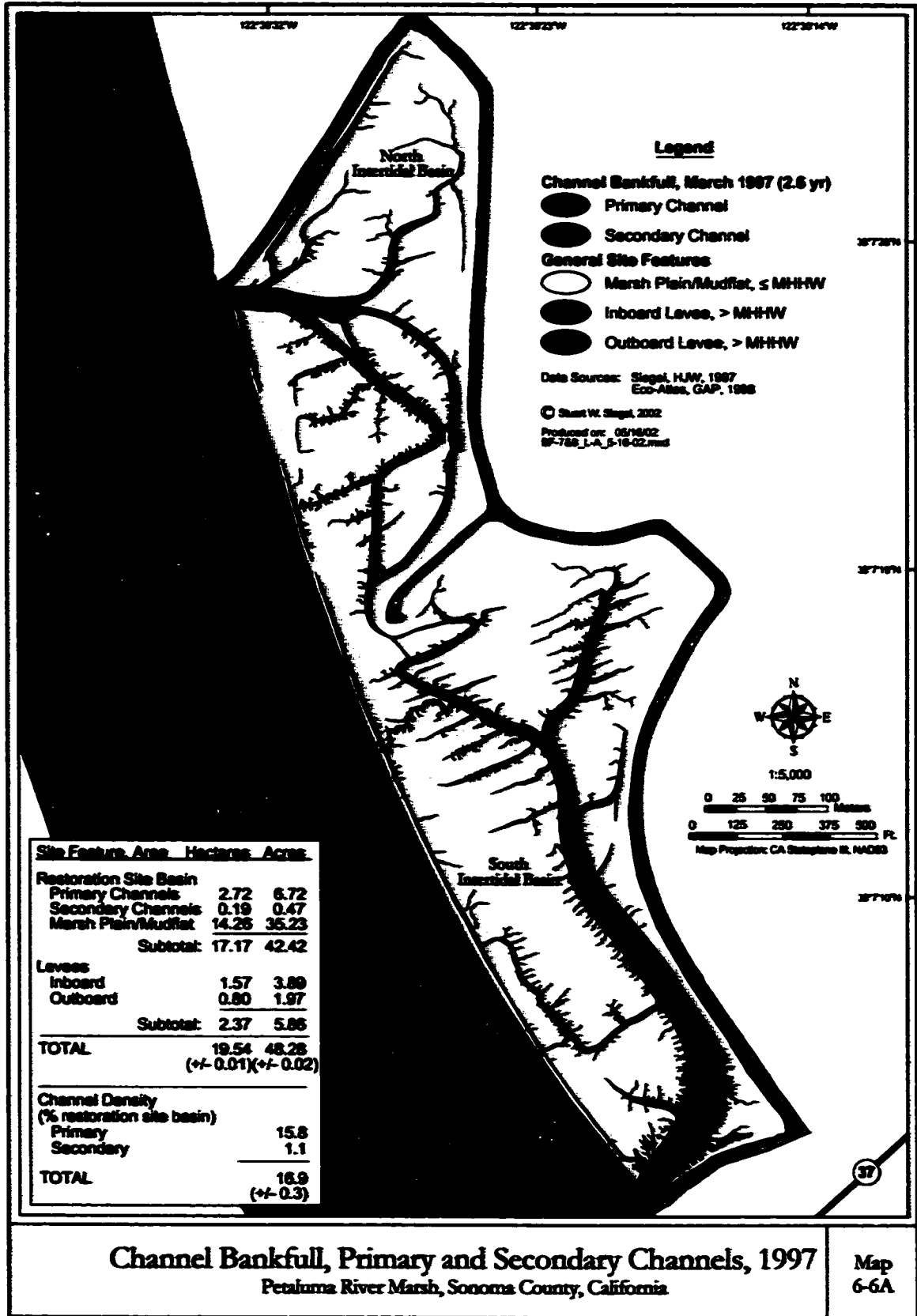
At the North Breach over time, the Shreve magnitudes for the full channel network were 462, 905, and 455 for 1997, 1998, and 1999, respectively. At the South Breach, these values were 646, 1386, and 624 (Map 6-4). In contrast for the primary channel-only network, these values drop to 38, 43, and 20 for the North Breach and 48, 42, and 34 for the South Breach for 1997, 1998, and 1999, respectively (Map 6-5). These data reveal a number of important results.

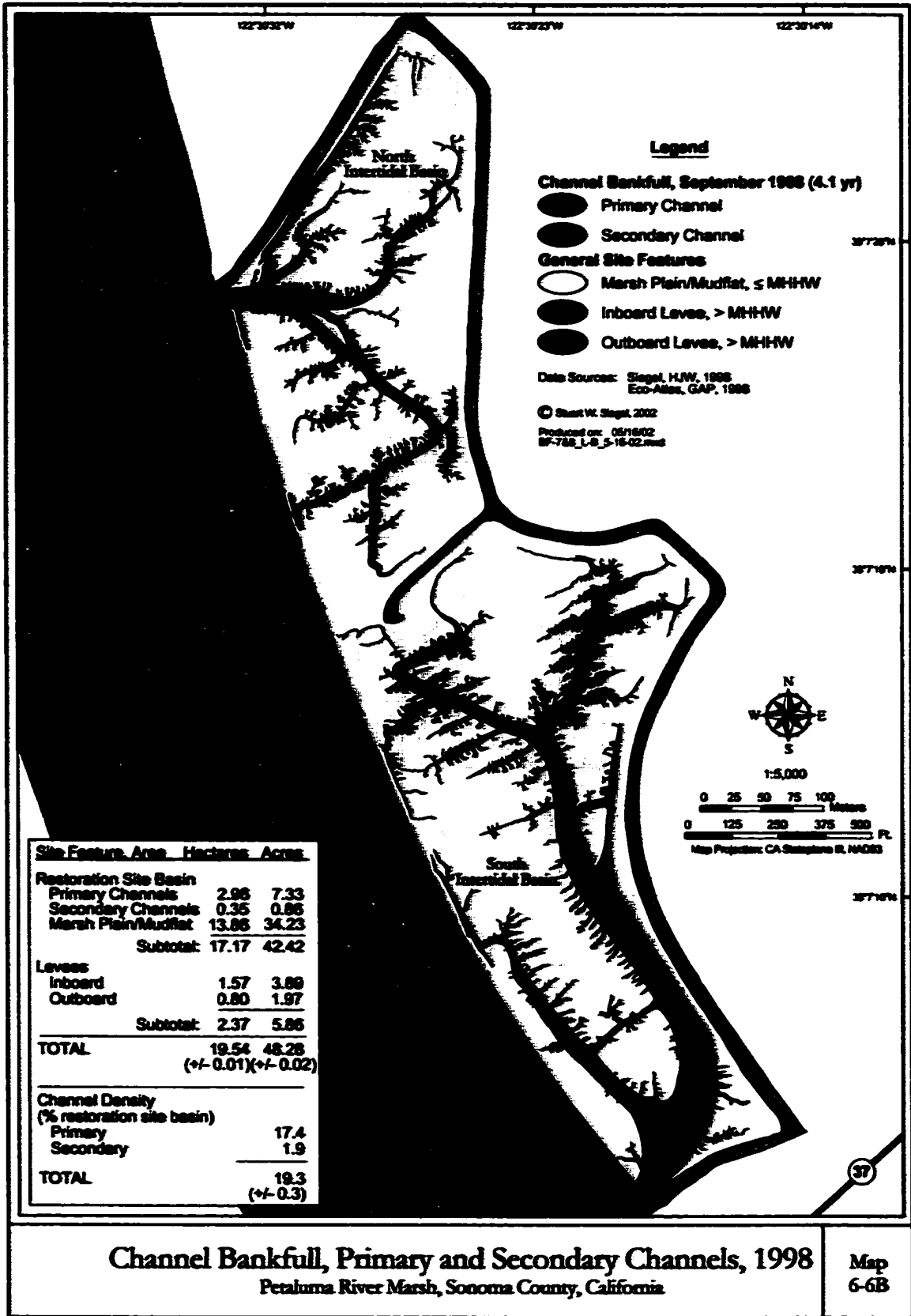
Scale Dependency. First, the results are vastly different depending on scale, as revealed by the full network versus primary network only. The scale at which only primary channels are detected and mapped in a quantitative manner is the scale that most remote sensing applications would operate because of its considerably lower cost for data acquisition and processing and the ability to analyze larger areas at a reasonable cost. Only site-specific monitoring efforts might collect data at the scale comparable to that used here for quantifying the secondary channels.

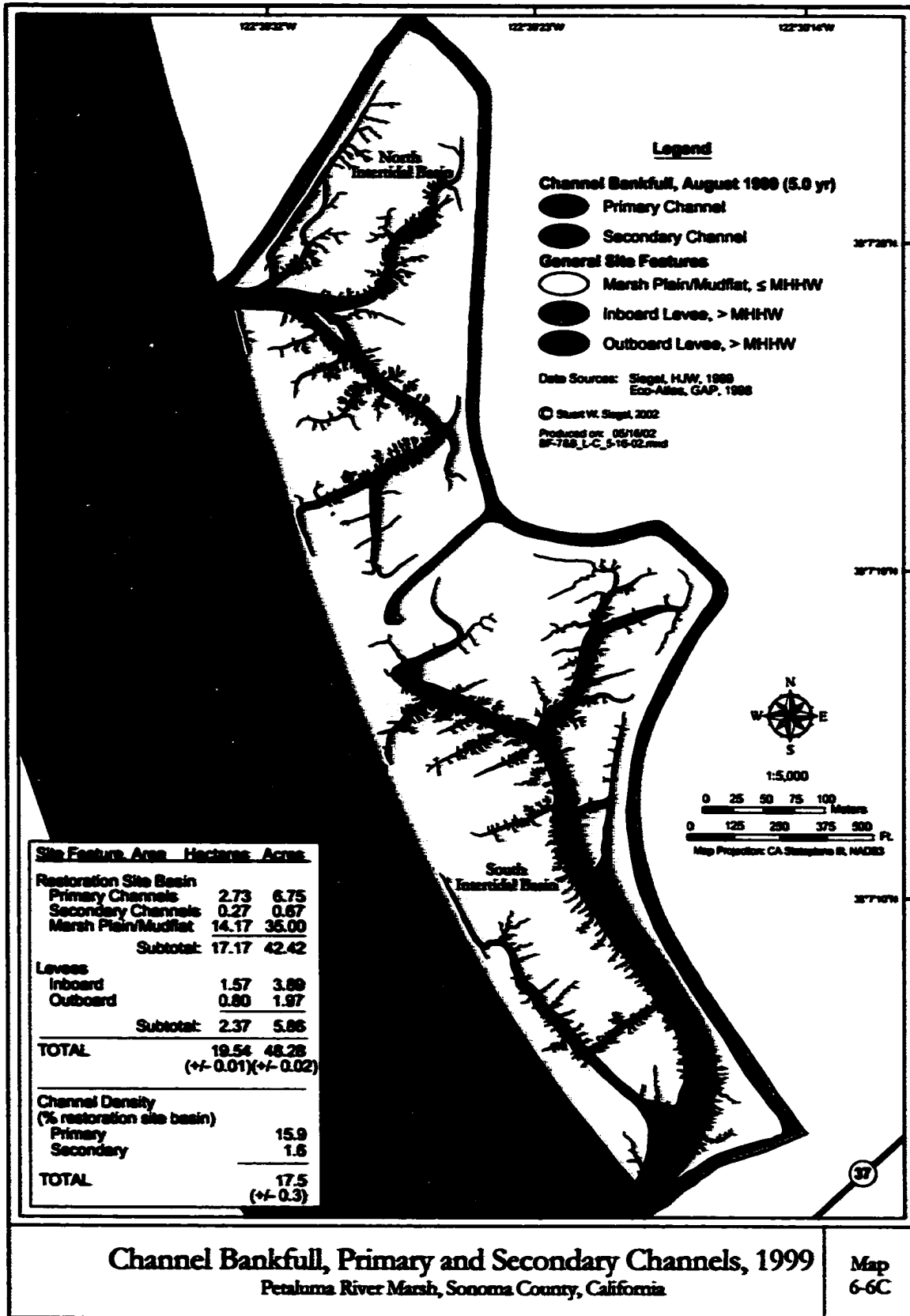
Temporal and spatial changes in full network Shreve magnitude. Second, full network Shreve magnitude increased to a peak from 1997 to 1998 then retreated by

1999. Shreve magnitudes essentially doubled from 1997 to 1998. From 1998 to 1999, these values dropped by half, back almost identical to the original value. During the growth period, nearly 1,200 small secondary channels formed naturally. A vast majority of these secondary channels were small rills normal to larger primary channels. During the declining period, about the same number of secondary channels disappeared, being filled with sediment and incorporated into the evolving marsh plain. Map 6-2 shows the spatial pattern of secondary channel gains and losses from year to year, and Map 6-6 shows where these channels were located each year.

For the South Basin, secondary channels were located disproportionately closer to the levee breach in 1997, where ground surface elevations were higher than farther from the breach (Map 6- 6). In 1998, that pattern reversed, with hundreds of new secondary channels located far from the breach and reduction in numbers close to the breach. Following the large overall drop in secondary channel numbers in 1999, the remaining channels were distributed relatively evenly throughout the South Basin.







For the North Basin, secondary channels were located disproportionately in the southern part of the basin in 1997. The doubling of channels by 1998 occurred throughout the basin, leading to relatively uniform secondary channel spatial distribution. The subsequent halving of channels to 1999 occurred throughout the basin but with those areas farthest from the breach (the northern part predominantly and the southern part lesser so) undergoing somewhat greater loss. The result by 1999 was a secondary channel spatial distribution weighted more toward the center of the basin with the farther reaches having fewer secondary channels.

Temporal and spatial evolution in primary channel-only network complexity. Primary channel-only complexity underwent far less change minimally during the research period (Map 6-1).

6.4.2 Strahler Order

The channel Strahler order allows calculation of branching (bifurcation ratios) in the channel network (e.g., Strahler 1964, Allen 2000b). In tidal marshes, multiple channel bifurcation is one geomorphic mechanism that allows for tidal circulation throughout much of the marsh plain (Eisma 1998, Allen 2000b). Strahler order is also commonly used to infer channel size (e.g., Coats *et al.* 1995, Allen 2000b) regardless of appropriateness but, as the data in Table 6-1 show, such application can lead to erroneous quantification because of the scale dependency of the analysis.

Consequently, channel order should be used cautiously or not at all to describe channel size and the scale of its derivation should be reported along with the data.

Table 6-1 shows the number of channels of each Strahler order for each basin for the March 1997, September 1998, and August 1999 aerial photography events. Table 6-1 also divides the results into the full network (Table 6-1A and shown in Map 6-4) and the primary channels-only network (Table 6-1B and shown in Map 6-5).

Full Channel Network

There are a number of results for the full channel network. First and foremost, these data reveal a large temporal change in the number of channels of each order. The values for each order increase by a factor of 2 to 3 (depending on order) from March 1997 to September 1998 then revert back in August 1999 to values nearly identical to March 1997. About 1,000 small secondary "rill" channels appeared on the site by September 1998 and disappear by August 1999. These channels account for a bulk of the increase and subsequent decrease.

Second, the channel order at each levee breach changes from 5th order in 1997 to 6th order in 1998 and back to 5th order in 1999 (compare Maps 6-4B to 6-4C and Maps 6-5B to 6-5C). During this period the channels that passed through each levee breach still drained the same watershed area, retained the same width, yet did undergo some adjustment in depth. The change in Strahler order reflects the accounting of the small, secondary channels on the results of a Strahler order analysis.

Third, the data in Table 6-1A and the network shown in Map 6-4 suggest a very similar channel network in 1997 and 1999 and a different network in 1998. Comparing 1997 to 1999 shows a very similar numbers of channels of each order and a fairly similar spatial distribution of these channel orders. However, as will be presented below, a number of other channel network attributes are not similar between 1997 and 1999, suggesting that a Strahler order analysis only does not provide a sufficient characterization of channel networks. Though not surprising, this result is important because of the reliance in tidal marsh restoration design on Strahler order as a quantitative attribute of the channel network (e.g., Coats *et al.* 1995), suggesting that its use should be applied cautiously.

Primary Channel-Only Network

The primary channel-only network describes the system of relatively large channels at the site, generally at least 2-3m minimum width. Photo 6-3 shows two types of primary channels and the secondary channels. Looking southwest from the inboard levee, this photo shows in the distance the southern section of pilot channel through the North Basin. This type of primary channel is characterized by broad, flat-bottom channels dissected by a narrow thalweg (usually <0.2m wide) and relatively abrupt channel banks. Traversing the image horizontally in the foreground is the second type of primary channel, a narrow (<1m) yet lengthy channel with a defined thalweg junction to the pilot channels. Perpendicular to this latter type of primary channel are several secondary channels, each about 0.2-0.3m in width and <3m in length.

Photo 6-3. Primary and Secondary Channels in North Basin, 22-May-1998



This photograph shows secondary channels in the foreground intersecting a small primary channel (traversing left to right across the lower portion of the photograph), all of which drain into the much larger primary channel (part of the North Basin pilot channel) visible in the background. View WSW from inboard levee near multi-channel junction just north of the central levee.

The Strahler order analysis for the primary channel-only network reveals a very different picture than that from the full channel network, not a surprising result. First, the total number of first order channels drop dramatically relative to the full network: from 1,108 to 86 for 1997; from 2,291 to 85 for 1998; and from 1,079 to 54 for 1999. These drops represent the number of small, secondary channels that are excluded from the primary channel-only network, and it conveys the degree to which the scale of analysis influences the results.

Second, temporal patterns show a very different picture than the full network. The primary channels are far larger, represent a bulk of the network volume, and change in size far more slowly and thus are less likely to appear and disappear in short time periods. For each channel order between 1997 and 1998, the total number and basin distribution of channels remained fairly stable, suggesting very little change in the channel network (Map 6-5 shows the similarity well). However, during that same period, the site filled with an additional $50 \times 10^3 \text{ m}^3$ ($75 \times 10^6 \text{ kg}$) of sediment (about 20% of total accretion to that date; Table 5-2) and the number of secondary channels doubled. In those two years, each levee breach represented a fourth order channel network. In contrast, 1999 reveals a very different network as described by a Strahler order analysis. Both basins dropped from fourth to third order systems, driven by loss of small, first order channels high in the basin. In the South Basin case, this drop originated from the loss of a single, very small channel near the PG&E tower. The actual channel geometry at each breach remained fairly stable and did not change by the large degree that a order change might suggest were it any indicator of channel size.

As a network descriptor, Strahler order examines only channel centerline characteristics such as branching (bifurcation ratio) and length (length ratio) but not channel size. However, marsh restoration practitioners continue to use it, erroneously, to describe or quantify channel size (e.g., Coats *et al.* 1995, Zeff 1999). The data in Table 6-1 and Map 6-5 can show where a channel goes around the site but without geometric data we cannot assess the network's function as a material transport vessel.

Because the marsh restoration field commonly uses Strahler order in a quantitative, design manner, these results are important in demonstrating that such a design approach does not have a valid quantitative basis.

6.4.3 Bifurcation Ratio and Sinuosity

The bifurcation ratio quantifies channel branching and sinuosity quantifies the degree of meandering in a channel. These two geomorphic characteristics together help to describe the extent to which a channel network provides its circulatory function by accessing the tidal marsh plain (Allen 2000b, French and Reed 2001). Bifurcation ratio and sinuosity are also used to classify estuarine tidal channels (e.g., Eisma 1998). Therefore, understanding the bifurcation and sinuosity characteristics in a restoration site helps to inform the degree to which desired ecological outcomes can be promoted.

Full Channel Network Bifurcation

Bifurcation ratios ranged from 2.00 to 6.53, with averages across channel orders ranging between 4.65 and 5.18 (Table 6-1). Table 6-1 dissects these averages to reveal a large difference in their variances; the sixth order designation for both basins in 1998 creates a much greater variance while 1997 and 1999 are fairly similar. Also notable is that the individual ratios comprising the averages are fairly similar between 1997 and 1999.

Table 6-2 presents these data in a comparative context with other tidal marshes around the world and it presents the overall average bifurcation ratios at the site spanning all three periods and all channel orders. The range of bifurcation ratios observed at the study site is larger than that for the other marshes quantified; those marshes ranged from 3.03 to 5.45. The overall average bifurcation ratio for the full channel network at the study site was 4.69, higher than the averages from the other marshes (which ranged between 3.84 and 4.35). These results offer one small piece of information suggesting that the channel network at the study site may evolve into one that meets its functional goals. However, bifurcation alone does not allow one to reach that conclusion.

Primary Channel-Only Network Bifurcation

Bifurcation ratios ranged from 2.00 to 6.86, with averages ranging between 3.38 and 5.83 (Table 6-1). Comparing these data to marshes from elsewhere around the world (Table 6-2) shows that the overall average primary channel-only bifurcation ratio of 4.05 is in line with the range of 3.84 to 4.35 for other marshes, suggesting that the primary channel-only network is forming similar branching characteristics to natural marshes. The comparable result for the full channel network, 4.69, is greater than the other reported marsh values, which suggests that the results of the primary channel-only network analysis are more representative of data collected at other marshes. This result is not surprising, as the primary channel-only analysis uses a more commonly applied spatial scale for the analysis.

Sinuosity

I have not completed a sinuosity analysis for the study site but can make a qualitative analysis through aerial photography to a nearby natural marsh (Photo 6-4). That photograph shows a portion of the Petaluma Marsh, a large (900 hectare/2,300 acre) Holocene tidal marsh located a short distance up the Petaluma River from the study site (see location in Map 3-3 in Chapter 3).

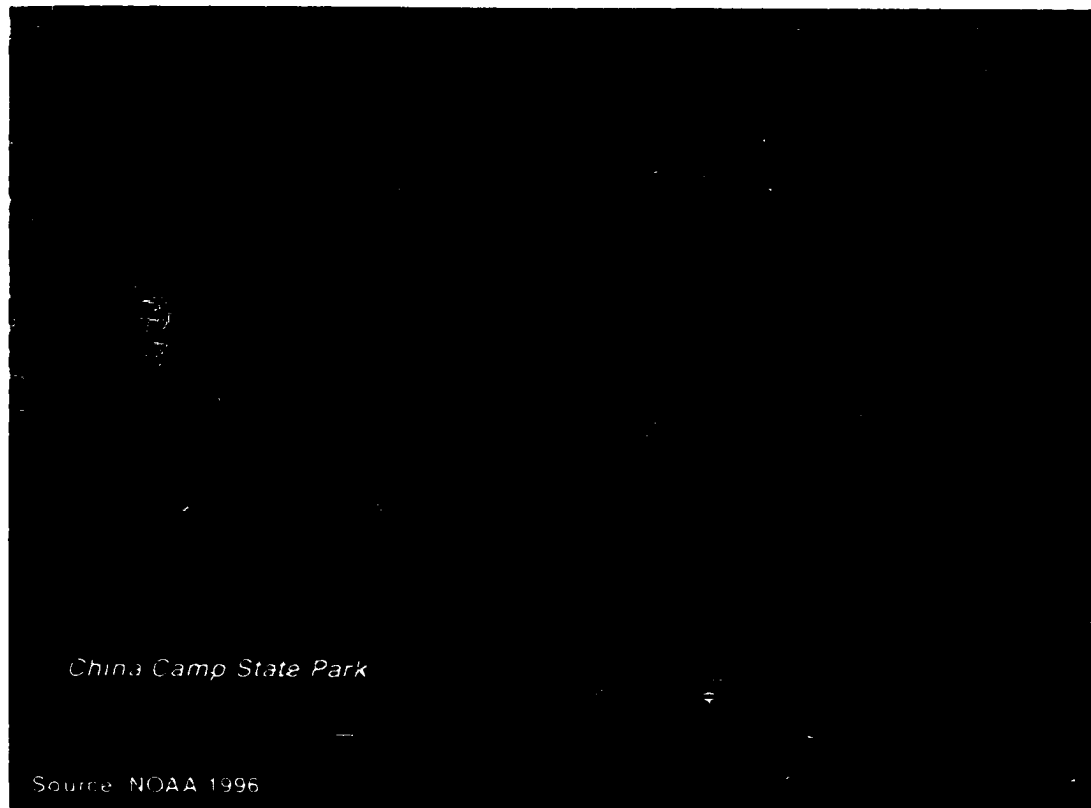
Photo 6-4. Portion of Holocene Petaluma Marsh Located Near Study Site



A visual comparison of the channel network in this photograph and the channel network at the study site shows that sinuosity is far higher in this ancient marsh. Such high sinuosity is a characteristic trait of tidal marshes around the globe (Eisma 1998, Allen 2000b).

Tidal marsh that naturally formed in the San Francisco Estuary over comparatively short time periods as a result of Sierra Nevada hydraulic mining debris accumulation exhibit a very different sinuosity regime. Photo 6-5 shows marshes at China Camp State Park, in the southwest corner of San Pablo about 12 kilometers (7.5 miles) from the study site (Map 1-1 in Chapter 1). The high sinuosity in the Holocene-era portion of the marsh versus the low sinuosity in the recently-formed marshlands have been attributed to the relative steepness of the recent marshlands and the rapid rate of accretion (Eisma 1998, French and Reed 2001). Gabet (1998) evaluated channel meander in China Camp and found that although channel bank slumping does occur, it did not appear to represent the dominant mechanism generating high sinuosity. Eisma (1998) and Atwater *et al.*(1979) have suggested that the slow marsh formation into flooded uplands during periods of sea level rise during the Holocene may have provided a mechanism for generating high sinuosity, as it is a common attribute of ancient marshes around the world.

Photo 6-5. Holocene and Recent Tidal Marshes at Nearby China Camp State Park



China Camp tidal marshes exhibit high sinuosity in the Holocene-era marshlands and low sinuosity in the marshes that accreted relatively rapidly from the hydraulic mining debris. The dashed line approximates the shoreline prior to this accretion.

6.4.4 Centerline Length

Channel centerline length is one component measure of channel geometry (width and depth data complete that geometry). Table 6-1 lists centerline lengths by each channel order for each basin each year and for the total network and primary channels-only network. Centerline length is necessary to calculate length ratios and linear network densities for use in comparing the channel network at the study site to other marshes.

Full Channel Network

Total centerline length was 10.0km in 1997, 12.8km in 1998, and 9.3km in 1999. The South Basin/North Basin relative contributions to these total lengths were about 1.5:1 in 1997 and 1999 versus 1:1 in 1998. The South Basin total length started at 6.1km in 1997, climbed to 6.4km in 1998 (+5%), and dropped 5.4km by 1999 (-15%). In contrast, the North Basin started at 4.0km in 1997, jumped to 6.3km in 1998 (+58%), then dropped back to its starting point at 3.9km in 1999 (-38 %).

Primary Channel-Only Network

Total centerline length was 6.0km in 1997, 5.5km in 1998, and 4.3km in 1999. The South Basin/North Basin relative contributions to these total lengths varied from 1.4-1.7: in all three years. In other words, primary channel lengths underwent a steady decline in both basins, indicating an overall reduction in channel network spatial extent and volume.

6.4.5 Channel Surface Area

Channel surface area provides a more informative channel network indicator, as it measures cumulative channel width and length and it is the input value for calculating channel areal density (see next Section). Its variability between the North and South Basins and over time can illuminate geomorphic processes in the evolving marsh. Table 6-1 provides channel areal data for primary and secondary channels and the

ratio of these two channel categories. Area ratio of primary to secondary channels describes the relative contribution of each channel type to total surface area.

Primary channels covered 2.72, 2.97, and 2.73 ha (6.72, 7.33, and 6.75 ac) in March 1997, September 1998, and August 1999, respectively. The South Basin contained 64%, 71%, and 71% of the primary channel surface area during those respective times. The constant ratio from 1998 to 1999 coincides with a nearly 10% drop in actual surface area back to the 1997 extent. Secondary channels covered 0.19, 0.35, and 0.27 ha (0.46, 0.86, and 0.66 ac) in 1997, 1998, and 1999, respectively. The South Basin contained 63, 63, and 52% of the secondary channel surface area during those respective times. The constant ratio from 1997 to 1998 accompanied a nearly doubling of the surface area, meaning that the South Basin received 63% of the net newly formed secondary channels.

Area ratio values underwent large temporal and spatial changes. The highest values, indicating a predominance of primary channels, occurred in March 1997: South Basin 14.2 and North Basin 15.1. September 1998 had the lowest ratios, 9.5 and 6.8 for South and North Basin, respectively, reflecting the near doubling of secondary channel surface area combined with a 15% decline in North Basin primary channel area. August 1999 exhibited strong basin differences, with South Basin at 13.9 (back to 1997 levels) and North Basin at 6.2 (retained at 1998 levels). Primary channels provide greater ecological and marsh functions at this site because they represent a vast majority of the channel network volume and thus transport the most material.

6.4.6 Areal and Linear Channel Density

Channel density is perhaps the most informative descriptor of a tidal channel network, for it can describe “how much” channel exists and, in combination with other descriptors, inform the extent to which a restoration project is evolving toward meeting its ecological goals. Channel networks serve a vital function in tidal marshes. The ability to restore these networks to extents comparable to natural tidal marshes is an important objective for restoration practitioners. Measures that promote a larger channel network are thus important to identify. Too small a channel network has been identified as one of several problems tidal marsh restoration projects encounter (Callaway 2001, French and Reed 2001).

Channel density can be measured in three manners: (1) areal density expressed as percent of marsh surface area comprised of channels, (2) linear density expressed as length divided area, and (3) volume density expressed as percent of total tidal prism. Volume density was presented in Figure 4-4 in Chapter 4, which shows that that channel volume decreased only slightly during the monitoring period but that percent of total volume increased due to decreased marsh plain tidal prism.

Areal density describes the bankfull footprint of the channel network, integrating channel width and length geometry. It is one of several indicators describing “how

much" channel is present in a restoration project, an important issue in tidal marsh restoration (Callaway 2001, French and Reed 2001). It has been used recently by the San Francisco Airport runway expansion wetland mitigation planning team to assess what total wetland acreage would need to be restored to provide a given acreage of subtidal channel (Brad Hall, presentation, 2001). However, channel areal density is not commonly reported in the tidal marsh literature.

Linear channel density describes the amount of channel centerline dissecting a marsh plain per unit area. Where the described area consists of channels that are fairly large volumetrically, such as most primary channels, linear density serves as an important indicator of channel network extent. Conversely, where the described area consists of small yet lengthy channels, such as most secondary channels, linear density does not provide an informative indicator of network extent.

These two density indicators can be quantified separately for the full channel network and the primary channel-only network. Table 6-1 presents the channel density data and Table 6-2 compares these results to marshes elsewhere.

Linear Density

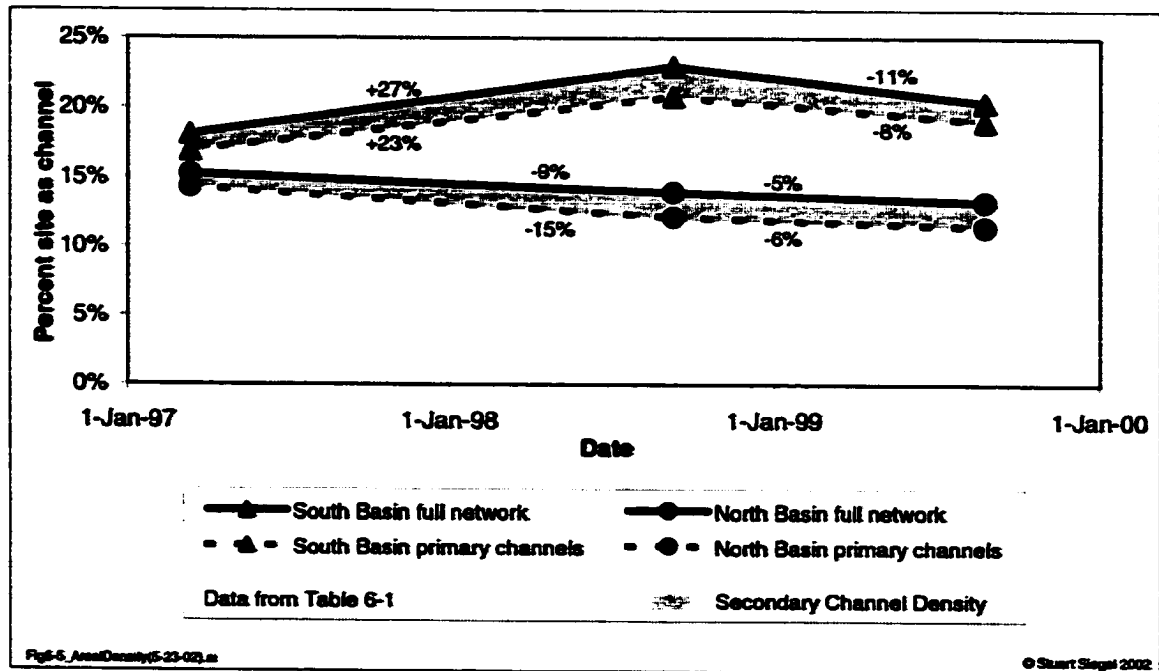
Linear density ranged from 52.7 to 91.2 and averaged 63.3 km km⁻² for the full network and 22.8 to 36.7 with an average of 30.7 km km⁻² for the primary channel-only network (Table 6-2). These results are within the combined range reported by four other researchers of 15 to 149 with average values ranging from 29.5 to 87.6 km

km⁻². Following the approach that the primary channel-only network represents a vast majority of the network volume, then the linear density results indicate that the study site is on the lower end of the range and averages compared to these other marshes.

Areal Density

The channels occupied from 11.4 to 23.0% of the total surface area at the site (Figure 6-5). Basin differences were present throughout the study period, with the South Basin areal density always exceeding that for the North Basin.

Figure 6-5. Primary and Full Channel Network Areal Density, 1997 to 1999



Grey shaded upper segment represents secondary channels; lower dashed line shows areal densities for primary channels that make up most of the total channel area.

6.5 Channel Formation and Initial Conditions of Small Parallel Berms

Following restoration of tidal action, many channels have formed through natural processes across the site. One of the primary questions is whether the initial conditions of small, parallel berms promoted natural channel formation and thereby increased the channel network extent relative to omitting these berms.

Two observations derive from the mapped data (e.g., Map 6-1) complement the numerical data presented in the previous sections. First, the parallel sets of berms guided the location of naturally forming medium-size primary channels in the South Basin. Second, most of these primary channels have persisted, though some have been lost through drainage capture as the site accreted.

Figure 6-6 shows the channel linear density for all naturally formed channels, organized by type (primary and secondary), basin (north and south), initial conditions (with or without small parallel berms), and year (1997, 1998, and 1999). Data plotted in Figure 6-6 exclude the pilot channels, as they are formed through pilot channel adoption. Linear density is chosen for representation because of its comparability to other reported data (e.g., Coats *et al.* 1995, Allen 2000b) and because, as described above in Section 5.5.7, linear density provides a meaningful indicator of channel network magnitude for primary channels.

Table 6-3 presents the density data plotted in Figure 6-6 and Table 6-4 contains the significance test results for selected comparisons. Error bars represent $\pm 95\%$ confidence interval and the color of the comparison bar represents significance level of the comparison (yellow = not significant, blue = significant, $p < 0.05$). Uncertainty reflects propagated method accuracy values (e.g., accuracy of deriving channel centerline lengths and delineating and calculating surface areas).

The comparisons chosen provide a means to examine the question posed for this chapter, *how initial geomorphic conditions influenced the geomorphic evolution of the channel network and the adjacent developing tidal marsh plain*. There are three comparisons to make:

- **Presence/absence of berms in each basin** is the primary effect to be measured
- **Basin effect with berms** is a secondary effect to help understand results of the primary effect by evaluating whether or not a difference exists between North and South Basin in areas that included berms
- **Basin effect without berms** is a secondary effect to help understand results of the primary effect by evaluating whether or not a difference exists between North and South Basin in areas that excluded berms.

An effect can be measured in two ways: as the density difference (A-B) between comparisons and as the density ratio (A/B). Determining whether results are statistically significant at the $p < 0.05$ value for each of these measurements entails a different test.

Difference test is a two-tailed, two-sample t test (Zar 1984, p.125) with the following null and alternate hypotheses:

$$H_0: \mu_1 = \mu_2$$

$$H_A: \mu_1 \neq \mu_2$$

where

μ_i = calculated density for each comparison value.

Ratio test is a one-tailed, one-sample t test (Zar 1984, p.98) with the following null and alternate hypotheses:

$$H_0: \mu \geq 0$$

$$H_A: \mu < 0$$

where

μ = calculated ratio – 1

which measures whether the ratio differs from 1:1 or no effect.

Figure 6-6. Channel Linear Density, Naturally Formed Channels by Type, Basin, Initial Conditions, and Year

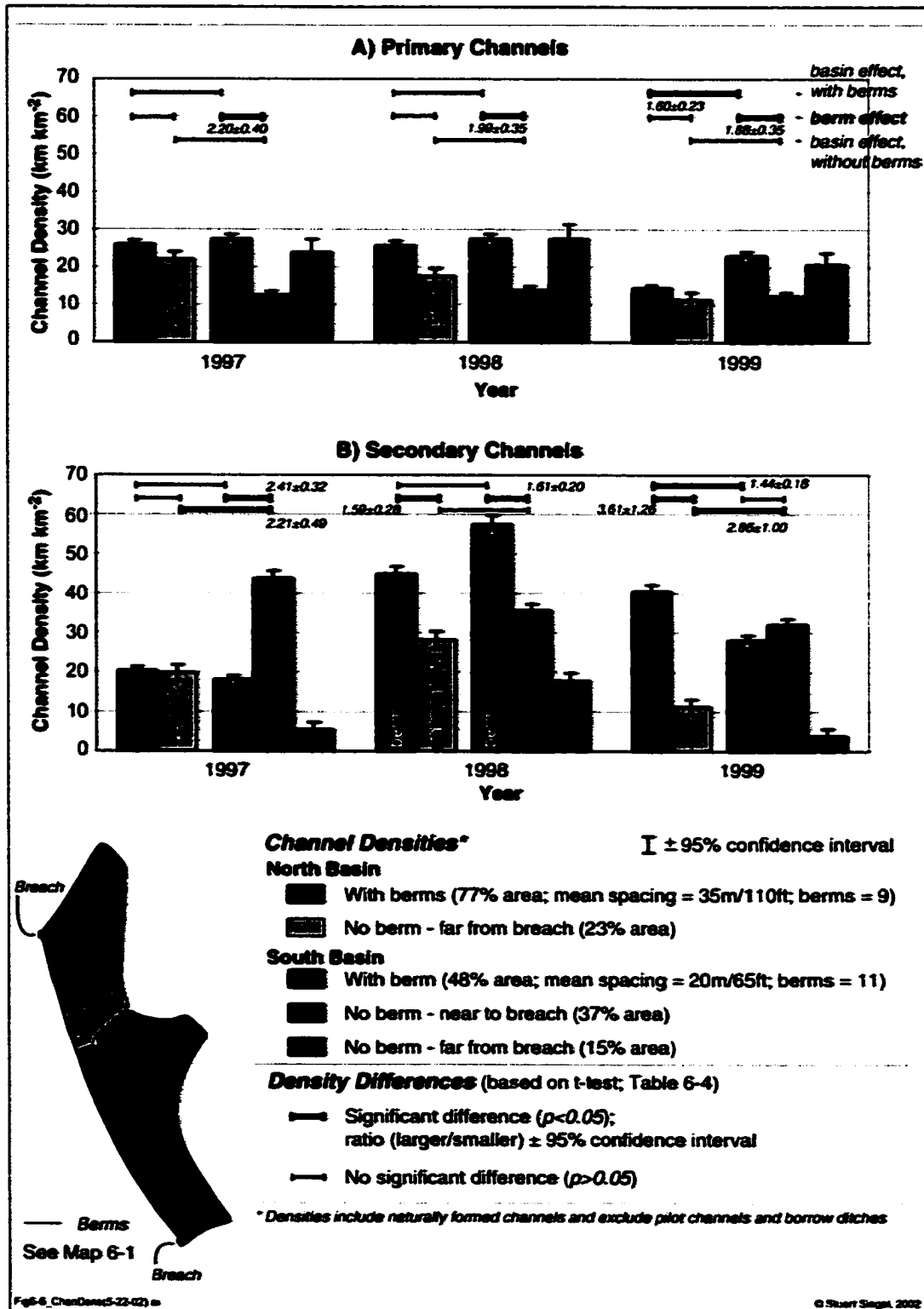


Table 6-3. Channel Linear Density of Naturally Formed Channels

Channel No	Centerline Length ¹		Channel Density ²			Channel Density ²			Area		% of Basin	
	Berm Year	(ft)	(m)	(mi km ²)	Std Error ³	95% CI ⁴	(km km ²)	Std Error ³	95% CI ⁴	(ac)		(ha)
A) SOUTH BASIN												
Areas for each type of initial condition												
With berms										12.04	4.87	48%
No berms -- near to breach										9.33	3.78	37%
No berms -- far from breach										3.88	1.57	15%
Primary channels (excludes pilot channel and borrow ditches)												
With berm												
1997	4,383	1,336	44.1	1.2	2.4	27.4	0.6	1.3				
1998	4,384	1,339	44.2	1.2	2.4	27.5	0.6	1.3				
1999	3,676	1,120	37.0	1.1	2.2	23.0	0.6	1.1				
No berm -- near to breach												
1997	1,541	470	20.0	1.2	2.3	12.4	0.5	1.0				
1998	1,708	520	22.2	1.2	2.3	13.8	0.5	1.1				
1999	1,512	461	19.6	1.2	2.3	12.2	0.5	1.0				
No berms -- far from breach												
1997	1,228	374	38.4	3.5	6.8	23.8	1.8	3.5				
1998	1,415	431	44.2	3.8	7.4	27.5	2.0	3.9				
1999	1,062	324	33.2	3.3	6.4	20.6	1.6	3.2				
Secondary Channels												
With berm												
1997	2,895	882	29.1	1.0	2.0	18.1	0.5	0.9				
1998	9,173	2,736	92.4	2.1	4.0	57.4	1.2	2.4				
1999	4,478	1,365	45.1	1.2	2.4	28.0	0.7	1.3				
No berm -- near to breach												
1997	5,415	1,650	70.4	1.8	3.5	43.7	1.0	1.9				
1998	4,412	1,345	57.3	1.6	3.1	35.6	0.8	1.6				
1999	3,968	1,209	51.6	1.5	2.9	32.0	0.8	1.5				
No berms -- far from breach												
1997	277	84	8.7	2.5	4.9	5.4	1.0	1.9				
1998	915	279	28.6	2.6	5.0	17.8	1.0	2.0				
1999	194	59	6.1	2.5	4.9	3.8	1.0	1.9				
B) NORTH BASIN												
Areas for each type of initial condition												
With berms										13.30	5.38	77%
No berms -- far from breach										3.88	1.57	23%
Primary Channels (excludes pilot channel and borrow ditches)												
With berm												
1997	4,583	1,397	41.8	1.1	2.2	26.0	0.6	1.2				
1998	4,540	1,384	41.4	1.1	2.2	25.7	0.6	1.2				
1999	2,537	773	23.1	0.9	1.7	14.4	0.4	0.8				
No berms -- far from breach												
1997	1,130	344	35.3	2.6	5.1	22.0	1.1	2.1				
1998	904	276	28.3	2.6	5.0	17.6	1.0	2.0				
1999	584	178	18.3	2.5	5.0	11.3	1.0	1.9				
Secondary Channels												
With berm												
1997	3,590	1,084	32.7	1.0	1.9	20.3	0.5	1.0				
1998	7,922	2,415	72.2	1.7	3.2	44.9	1.0	1.9				
1999	7,135	2,175	65.0	1.5	3.0	40.4	0.9	1.7				
No berms -- far from breach												
1997	1,018	310	31.8	2.6	5.1	19.8	1.0	2.0				
1998	1,449	442	45.3	2.7	5.2	28.2	1.1	2.2				
1999	576	176	18.0	2.5	5.0	11.2	1.0	1.9				

Notes:

1. Channel centerline lengths exclude pilot channels and borrow ditches.
2. Channel density calculated as centerline length divided by area.
3. Standard error = propagation of systematic methodological uncertainty of 15m on centerline length and 1,000 m² on area.
4. 95% confidence interval = 1.96 * standard error

Table 6-4. Channel Density Difference and Ratio t Tests

Comparison and Year	From ¹		To ¹		Density Difference ²		Density Ratio ³					
	Area	Density SE	Area	Density SE	It ⁴	Significant ⁵	From / To	SE	CI ⁶	It ⁴	Significant ⁵	
	(km km ⁻²)		(km km ⁻²)									
A) PRIMARY CHANNELS												
1. Berm versus No Berm												
a) South Basin												
1997 Berm	27.4	1.3	No Berm-near	12.4	1.0	9.28	p<0.02	2.20	0.21	0.40	5.85	p<0.10
1998 Berm	27.5	1.3	No Berm-near	13.8	1.1	8.33	p<0.02	1.99	0.18	0.35	5.58	p<0.10
1999 Berm	23.0	1.1	No Berm-near	12.2	1.0	7.23	p<0.02	1.88	0.18	0.35	4.93	p<0.10
b) North Basin												
1997 Berm	26.0	1.2	No Berm	22.0	2.1	1.68	no	1.18	0.12	0.24	1.47	no
1998 Berm	25.7	1.2	No Berm	17.6	2.0	3.51	no	1.46	0.18	0.35	2.58	no
1999 Berm	14.4	0.8	No Berm	11.3	1.9	1.45	no	1.27	0.23	0.44	1.18	no
2. North Basin versus South Basin												
a) Berms												
1997 North Basin	26.0	1.2	South Basin	27.4	1.3	0.84	no	1.06	0.07	0.13	0.82	no
1998 North Basin	25.7	1.2	South Basin	27.5	1.3	1.03	no	1.07	0.07	0.14	1.00	no
1999 North Basin	14.4	0.8	South Basin	23.0	1.1	6.34	p<0.05	1.60	0.12	0.23	5.12	p<0.10
b) No Berms ("near" area for South Basin; see Figure 6-6)												
1997 North Basin	22.0	2.1	South Basin	12.4	1.0	4.12	no	1.76	0.22	0.43	3.48	p<0.10
1998 North Basin	17.6	2.0	South Basin	13.8	1.1	1.67	no	1.27	0.18	0.34	1.57	no
1999 North Basin	11.3	1.9	South Basin	12.2	1.0	0.40	no	1.08	0.20	0.40	0.37	no
B) SECONDARY CHANNELS												
1. Berm versus No Berm												
a) South Basin												
1997 Berm	18.1	0.9	No Berm-near	43.7	1.9	11.95	p<0.01	2.41	0.16	0.32	8.58	p<0.05
1998 Berm	57.4	2.4	No Berm-near	35.6	1.6	7.53	p<0.02	1.61	0.10	0.20	6.13	p<0.10
1999 Berm	28.0	1.3	No Berm-near	32.0	1.5	2.04	no	1.14	0.07	0.15	1.92	no
b) North Basin												
1997 Berm	20.3	1.0	No Berm	19.8	2.0	0.24	no	1.03	0.12	0.23	0.24	no
1998 Berm	44.9	1.9	No Berm	28.2	2.2	5.78	p<0.05	1.59	0.14	0.28	4.21	p<0.10
1999 Berm	40.4	1.7	No Berm	11.2	1.9	11.32	p<0.01	3.61	0.64	1.26	4.08	p<0.10
2. South Basin versus North Basin												
a) Berms												
1997 South Basin	18.1	0.9	North Basin	20.3	1.0	1.63	no	1.12	0.08	0.16	1.54	no
1998 South Basin	57.4	2.4	North Basin	44.9	1.9	4.11	no	1.28	0.08	0.15	3.69	p<0.10
1999 South Basin	28.0	1.3	North Basin	40.4	1.7	5.80	p<0.05	1.44	0.09	0.18	4.93	p<0.10
b) No Berms												
1997 North Basin	43.7	1.9	South Basin	19.8	2.0	8.55	p<0.02	2.21	0.25	0.49	4.89	p<0.10
1998 North Basin	35.6	1.6	South Basin	28.2	2.2	2.73	no	1.27	0.11	0.22	2.32	no
1999 North Basin	32.0	1.5	South Basin	11.2	1.9	8.52	p<0.02	2.86	0.51	1.00	3.64	p<0.10

Notes:

- Channel density and standard error data from Table 6-3.
- Density difference measures the increase or decrease in channel density by treatment; difference must exceed uncertainty to observe effect.
- Density ratio, calculated as larger density/smaller density, measures whether the treatment (berm/no berm and north/south basin) increases channel density; ratio = 1 means no effect.
- Calculation of "t" value:
 - Ratio test (1-tailed, 1-sample) from Zar (1984) p.98 eq.8.1
 - Difference test (2-tailed, 2-sample) from Zar (1984) p.125 eq.9.6a
- Critical "t" distribution values from Zar (1984 Table B.3 p.484)
 - Ratio test (v=1): Itb=3.078 = p<0.10; Itb=6.314 = p<0.05; Itb=12.706 = p<0.025
 - Difference test (v=2): Itb=4.303 = p<0.05; Itb=6.965 = p<0.02; Itb=9.925 = p<0.01
- 95% confidence interval = 1.96 * standard error

6.5.1 Primary Channels

The following discussion pertains to the naturally formed channels. The analyses presented in Tables 6-3 and 6-4 and Figure 6-6 exclude the constructed pilot channels and the levee-parallel borrow ditches.

Berm Effect

In the South Basin for all three years, the presence of berms doubles the naturally formed primary channel linear density and this difference is significant at $p < 0.05$. In contrast, the North Basin had no significant berm effect at $p < 0.05$ (Figure 6-6A and Table 6-4). However, unlike the South Basin, North Basin had a no-berm area only at its headward extent and 77% of the area had berms versus 48% for the South Basin. Consequently, the findings for the North Basin do not necessarily provide much insight. The South Basin data are the fundamental results sought to answer the question posed for this chapter.

Basin Effect, with Berms

Areas with berms in both basins had similar naturally formed channel linear densities in 1997 and 1998, indicating no basin effect between those years. In 1999, the South Basin had 1.6 times as much density as the North Basin, significant at $p < 0.05$. This latter condition reflects nearly 50% reduction in channel density from 1998 to 1999 in

the North Basin. Again, the different berm configuration between the basins greatly limits the extent to which these data can be interpreted.

Berm Orientation Effect

North Basin has a complicating factor of berm orientation relative to the levee breach, a situation not present in the South Basin. The channel connecting the Petaluma River to North Basin is a straight channel for about 50m through tidal marsh on the river side of the outboard levee (see Map 1-2, in Chapter 1). Flows through this channel presumably have the highest velocities in the basin. Once inside, the core flow is oriented directly toward the inboard levee, and the pilot channel attempted to turn that core flow to the southeast.

Though ultimately successful with that goal, the early formation of a channel outside the pilot channel heading more directly toward the inboard levee (Map 6-1A) presumably occurred in response to this core flow being too strong for full conformance to the pilot channel. Orienting the small berms across this flow at about a 30° angle close to the breach and a 60° angle further into the basin subjected the berms to flow velocities likely to erode the incidentally constructed berm features. The November 1995 aerial photograph, 1.25 yr after restoration (Map 4-3A), shows eroded berms near the North Levee Breach. Consequently, berms in the North Basin available to exert a channel-forming effect were fewer than originally constructed.

One effect of this berm erosion is that the early-formed attempt to abandon the North Basin pilot channel (Map 6-1A) appears to cross multiple berms. However, because these berms have suffered erosion, they offer little if any geomorphic influence and consequently there really is no “crossing” of the berms. There is one small primary channel to the west of the pilot channel that crosses another berm that did not erode: that channel is the one exception, is relatively small, and its invert sits higher than the top of the berm.

The South Basin, in contrast, had the berms located a large distance from the highest velocities just inside of the levee breach. Consequently, those berms were not oriented in a manner that subjected them to such high flow velocities and erosion potential.

Basin Effect, without Berms

Areas with no berms in both basins did not show any significant differences in naturally formed channel density. Again, the different berm configuration between the basins greatly limits the extent to which these data can be interpreted.

Position within Basin Effect

In the South Basin, the area with berms is set back from the levee breach about 200m while one of the two areas without berms is near the breach and the other is far from the breach. Channels in the area far from the breach have extensive length but are very small (on the order of 0.2m wide and 0.1m deep) as they are at the headward reach of the system; consequently, that area is not considered to be a valid comparison. The

same situation and outcome applies to the North Basin, so no berm-effect conclusion can be drawn for the North Basin based on these data.

The no-berm area near the South Levee Breach occupies a similar spatial extent to the bermed area (37 vs. 48% of the South Basin; Figure 6-6) and is subject to full channel water and sediment transport because of its proximity to the breach. Yet, it has half the channel linear density of the bermed area. This difference is both statistically significant and quite apparent visually on the channel bankfull map (Map 6-1).

Berm Spacing Effect

Berm spacing in the South Basin averages 20m vs. 35m for the North Basin (Figure 6-6 and Map 6-1). No significant difference in channel density was observed in 1997 and 1998, indicating no effect on channel linear density from berm separation distance. However, by 1999 the density had declined by almost half in the North Basin with-berm area while the South Basin with-berm area experienced a much smaller decline. These data suggest that berm spacing may influence effectiveness at promoting channel formation. However, additional data would be necessary to determine whether these results continued over time and whether this effect is in fact due to the berm spacing due to confounding variables for the North Basin (described in Chapter 3). Visual examination of with-berm channel density in Map 6-1 between North and South Basin for each year does show a clearly greater density in the South Basin, especially by 1999.

6.5.2 Secondary Channels

Figure 6-6 shows that secondary channel linear density does not correlate to presence/absence of berms. Secondary channels form by a different mechanism than do primary channels (they are an erosional feature) and occupy a specific geomorphic position (at the boundaries of the mudflat/marsh plain). Secondary channel formation is discussed below.

6.6 Primary Channel Formation and Initial Conditions

The most plausible explanation of how berms affect natural channel formation is that the topographic variation created by berms concentrates ebb flows. Once water levels on the ebb tide drop to the height of the berm tops, then the remaining ebb flow occurs entirely between the berms and thus adjacent berms act as watershed divides. This process has the effect of generating a period of ebb flow focused (concentrated) between berms. It may be the case as well that the berms exert some flow direction control even with water levels above the berm tops, though this phenomenon was not explored in this research. Scour most commonly occurs on ebb flows (Dronkers and van Leussen 1988, Mehta 1993, Eisma 1998, Allen 2000b, Ruhl *et al.* 2001). Thus, this concentration of ebb flow between berms appears to generate sufficient boundary shear stress to exceed the erosion resistance of accreted sediments and channels are thereby formed and maintained.

The data presented in Section 6.5 and visual examination of the aerial photographs in Chapter 4 (Maps 4-2 and 4-3) and channel bankfull (Map 6-1) establish for the South Basin that berms promote natural channel formation leading to a higher density of channels in areas with berms versus without berms. This effect is more difficult to ascertain in the North Basin due to confounding effects of berms being spaced more widely (35m vs. 20m), berm orientation at angles to high velocity flows through the North Levee Breach, and lack of a no-berm area close to the breach to act as comparison to bermed areas elsewhere in the basin. The results between the two basins suggest but do not establish that closer berm spacing leads to higher channel densities. However, it makes sense that the closer the spacing the more channels would form, given the mechanism described above that may account for how the berms promote natural channel formation.

6.7 Secondary Channel Formation and Shallow Ebb Flows off Mudflat

Secondary channels form normal to primary channels along the sloping edges of the mudflat/primary channel interface. These channels form by scour under ebb sheet flow draining off the mudflat. Erosion potential is a function of the strength or resistance to erosion of the cohesive silts and clays. Newly deposited sediment has the least strength, whereas sediment that has sat in place over time has been subject to

compaction, consolidation, and desiccation that makes it more resistant to erosion (Mehta 1993, Black *et al.* 1998, Eisma 1998, Allen 200b). In the San Francisco Estuary, fresh deposits from winter and spring runoff events initially are relatively erodable in the spring and early summer months relative to later in the summer and fall (Ruhl *et al.* 2001).

Sheet flow duration is relatively brief and is controlled by the mudflat elevation and heights of sequential high and low tides. Distinct cutoff contours are visible along the banks of primary channels, with banks above the line being dissected by perpendicular secondary channels and below the line being smooth, undissected mud (this phenomenon is evident in Photo 6-3). Higher mudflat elevations mean less water to drain, which translates into shorter flow durations each ebb tide and thus less erosion potential overall.

Applying this inverse relationship predicts that secondary channel formation should be greatest in lower areas of the site. This prediction is confirmed through sequential consideration of the data presented in Map 6-2 (bankfull change between years), Map 4-8 (topography each year), and Map 5-1 (topographic change between years). Map 6-2 shows channel bankfull change illustrating where secondary channels formed. In the period between March 1997 and September 1998, secondary channel formation was most extensive in the lower areas in both basins, with a net gain of nearly 1,200 individual channels (Table 6-1). That value understates the total number of newly formed secondary channels because Map 6-2 also shows a large number of secondary

channels disappeared during that same period. In the South Basin alone, the distal (northern) reach comprised a majority of the newly formed secondary channels during that period (Table 6-1 count of first order channels).

Map 5-1 shows the spatial patterns of topographic change and if compared to Map 6-2 of bankfull change, helps to reveal confirming evidence of the topographic control on secondary channel formation.

Chapter 7.0 Conclusions

Since 1850, nearly 90% (about 60,000 hectares/150,000 acres) of San Francisco Estuary tidal marshlands have been diked and drained for agriculture, salt production, waterfowl management, and development. Resource managers envision restoring 22,000 to 27,000 hectares (55,000 to 65,000 acres) of these “diked baylands” to tidal marsh for natural resource conservation purposes. These lands have subsidence below marsh plain elevations, between 0.3-3m, presenting challenges for successful marsh restoration because tidal marsh elevations must be restored to provide target ecological functions. When opened to the tides, these sites become intertidal “basins” with net accretion rates strongly influenced by incoming sediment concentrations, wind fetch, storms, tidal currents, runoff, salinity, existing site landforms, baseline elevations, consolidation, compaction, desiccation, and biomass accumulation.

Several past restoration efforts have been mixed in meeting ecological goals, often due to channel networks inadequate to provide full circulation and elevations and substrate poorly suited for tidal marsh establishment. Resolving these problems is essential to meet the Estuary’s restoration goals.

This research examined temporal and spatial net sediment accretion patterns and the role of pilot channels and berms in controlling channel network evolution. Research included a field component to measure topographic features and to collect a 21-month record of water column physical parameters, a remote sensing component of stereo-

pair aerial photography at six-month intervals (three of five data sets used in the analysis spanning beginning, middle, end), a photogrammetry component to extract topographic data, a GIS component to extract and analyze data, and a numerical component to analyze data.

This research used the Petaluma River Marsh restoration project, a 19-hectare (47-acre) diked bayland in the northwest corner of San Pablo Bay (subsided to local mean lower low water elevation) restored August 1994. The study site and its restoration approach represent a specific yet common configuration in the San Francisco Estuary – diked, subsided baylands (nearly 2m in this instance) utilizing natural sedimentation to restore marsh elevations. The commonality of this configuration imparts general applicability of these research results to future restoration efforts in the region and elsewhere with a similar landscape setting. The site was effectively divided into two basins by construction of an access levee that crossed about 75% of site width.

Natural Channel Formation and Initial Condition of Small, Parallel Berms

The restoration project constructed a series of small, parallel berms about 1m tall by 2-3m wide, 20-35m apart, composed of cleared vegetation and surficial soils, and created incidental to excavating borrow soils from portions of the site for levee construction. These berms acted like multiple small “watersheds” within which channels formed naturally atop the deposited sediment (only the South Levee Breach retained pre-existing topography without sedimentation).

South Basin berms covered half the basin, were spaced 20m apart, and were located away from the highest tidal flow velocities associated with the breach. Channel density was significantly greater in the bermed area, showing that these simple construction features can have a positive effect on natural channel formation. The question remains regarding the longevity of the channel network as the site vegetates. Aerial photography and site visits after completion of this field study demonstrate channel persistence through spring 2002 when this dissertation was completed. It is likely that much but probably not all of the network will persist and it will be interesting to evaluate how vegetation colonization changes the network. This positive geomorphic outcome suggests an effective, low-cost, low-tech approach to promote higher channel densities and the ecosystem support functions those channels provide.

The North Basin berms covered three quarters of the basin with the no-berm area at the headwaters distal from the levee breach, were spaced 35m apart, and some were located across the peak tidal flow velocity path of the North Levee Breach. These factors combine to make it difficult to draw any significant results from the North Basin. All that can be stated is that channel areal densities declined steadily and remained below that for South Basin throughout the period monitored, and linear densities nearly equaled that of South Basin with-berm areas in 1997 and 1998 but dropped in 1999 to South Basin no-berm area levels.

Pilot Channels Exert Strong Influence

The restoration design included small pilot channels (0.3m deep by 3m wide) extending over 400m in the North Basin and 700m in the South Basin. These channels were intended to ensure low tide drainage and to promote channel network development. The pilot channels maintained planform position even while accreting sediment throughout their length. Minimal lateral migration occurred and channel widths experienced increases and declines. An early attempted abandonment of the North Basin pilot channel failed. Taken together, these results describe a positive influence of antecedent morphology on the creation and retention of larger channels within a network.

Mudflat/Marsh Plain Spatial-Temporal Accretion before Vegetation

Early accretion before vegetation colonization created surface gradients that sloped away from the levee breach, controlled by the inverse relationship between elevation and accretion rates, the drop in flow velocity inside the levee breach and around the accreting surface, and the timing within the flood tide of the maximum suspended sediment concentrations. The resultant accretion patterns are analogous geomorphically but of different origin to a prograding delta described for fluvial and coastal systems in which a depositional front proceeds laterally away from a sediment source, thereby creating a sloped ground surface. These results can be applied in a restoration context for predicting mudflat/marsh plain geomorphic evolution.

Interim Stable Elevations Prior to Vegetation Colonization

Site elevations leveled out initially at approximately 0.2m below local mean high water and roughly maintained those elevations through completion of the study period five years after restoration. These intermediately stable elevations occurred concurrent with ongoing sediment deposition and prior to much vegetation colonization. This apparent paradox is explained through the actions of physical processes that lower elevations: compaction, consolidation, and desiccation. Summer low-tide ground surface exposure coincides with the combined actions of strong winds, lengthy sunlight, and warm temperatures to maximize elevation-lowering desiccation. Once vegetation becomes established, as occurred after conclusion of this research, further elevation increases are expected and biotic processes then contribute to and moderate topographic adjustments. These results can be applied to other restoration efforts through consideration of initial site topography and the resultant ability of natural deposition, scour, and transport processes to shape the final marsh geomorphology, including both channels and the marsh plain.

Vertical Lifting of the Channel Network as the Site Accreted

The volume hypsographs derived from the digital elevation models show that, concurrent with ongoing site accretion, only slight channel network volume decreases occurred from 1997 to 1999 and that the relatively steady volume became positioned higher in the water column. In other words, tidal prism loss to accretion occurs almost entirely on the mudflat/marsh plain. As this network rose vertically with a near-constant volume, it experienced very little lateral migration, varying degrees of

fluctuating length and width, and the arrival and disappearance of small erosional “rills” along the mudflat/channel interface. These results support the hypothesis that antecedent morphology exerts a strong influence on network morphology, with antecedent including constructed channels and early naturally formed channels. Applied to a restoration design context, these results say that any approach that creates preferential flow paths could have a positive effect on promoting establishment of a functioning tidal channel network.

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Appendix A

Sediment Pin Field Data and Accretion Calculations

**Appendix A. Sediment Pin Field Data and Calculations
Petaluma River Marsh, Sonoma County, California**

Location	Date	Distance Pin Top to Ground Surface		Thickness Deposited Sediment ¹ (m)	Time Since Baseline (yr)	Deposition Rate			Ground Surface Elevation ²				Data Source	
		Method ⁵	(m)			Interval ³ (m/yr)	(m/yr)	Cumulative ⁴ (ft/yr)	(m MLLW)	(m NAVD)	(ft MLLW)	(ft NAVD)		
														(m)
SP-1	24-Aug-94	2.74	Rod	0.00	0.00	0.60	1.98	0.60	1.98	-0.09	-0.08	-0.29	-0.27	Wilcox ⁶
	14-Nov-96	1.40	Rod	1.34	2.23	0.16	0.63	0.55	1.80	1.26	1.26	4.12	4.14	Hueb ⁷
	8-Mar-97	1.35	Rod	1.39	2.64	0.09	0.30	0.44	1.45	1.31	1.31	4.26	4.30	UCB ⁸
	12-Dec-97	1.28	Rod	1.46	3.30	0.30	0.98	0.43	1.43	1.38	1.38	4.51	4.53	Siegel
	23-Feb-98	1.22	Rod	1.52	3.50	0.09	0.30	0.37	1.22	1.44	1.44	4.71	4.73	Siegel
SP-2	2-Dec-98	1.15	Rod	1.59	4.28	0.09	0.30	0.37	1.22	1.51	1.51	4.94	4.96	Siegel
	24-Aug-94	2.97	Rod	0.00	0.00	0.55	1.80	0.55	1.80	0.07	0.08	0.24	0.26	Wilcox ⁶
	14-Nov-96	1.75	Rod	1.22	2.23	0.42	1.37	0.53	1.75	1.29	1.30	4.25	4.27	Hueb ⁷
	8-Mar-97	1.62	Rod	1.35	2.64	0.12	0.39	0.44	1.43	1.42	1.43	4.67	4.69	UCB ⁸
	12-Dec-97	1.53	Rod	1.44	3.30	0.00	0.00	0.41	1.35	1.51	1.52	4.97	4.99	Siegel
SP-3	23-Feb-98	1.53	Rod	1.44	3.50	0.09	0.30	0.35	1.16	1.58	1.59	5.20	5.22	Siegel
	2-Dec-98	1.46	Rod	1.51	4.28	0.09	0.30	0.35	1.16	1.58	1.59	5.20	5.22	Siegel
	24-Aug-94	2.92	Rod	0.00	0.00	0.48	1.58	0.48	1.58	0.12	0.12	0.39	0.41	Wilcox ⁶
	8-Mar-97	1.70	Rod	1.22	2.64	0.09	0.30	0.39	1.28	1.34	1.34	4.39	4.41	UCB ⁸
	12-Dec-97	1.63	Rod	1.28	3.30	0.40	1.31	0.39	1.28	1.41	1.41	4.62	4.64	Siegel
SP-4	23-Feb-98	1.55	Rod	1.37	3.50	0.03	0.08	0.33	1.07	1.49	1.49	4.88	4.90	Siegel
	2-Dec-98	1.53	Rod	1.39	4.28	0.03	0.08	0.33	1.07	1.51	1.51	4.95	4.97	Siegel
	24-Aug-94	2.97	Rod	0.00	0.00	0.61	1.99	0.61	1.99	-0.12	-0.12	-0.41	-0.39	Wilcox ⁶
	14-Nov-96	1.62	Rod	1.35	2.23	0.19	0.63	0.56	1.82	1.23	1.23	4.03	4.05	Hueb ⁷
	8-Mar-97	1.56	Rod	1.41	2.64	0.12	0.39	0.45	1.48	1.29	1.29	4.22	4.24	UCB ⁸
SP-5	12-Dec-97	1.47	Rod	1.50	3.30	0.30	0.98	0.45	1.46	1.38	1.38	4.52	4.54	Siegel
	23-Feb-98	1.41	Rod	1.56	3.50	0.03	0.08	0.37	1.21	1.44	1.44	4.72	4.74	Siegel
	2-Dec-98	1.39	Rod	1.58	4.28	0.03	0.08	0.37	1.21	1.46	1.46	4.78	4.80	Siegel
	24-Aug-94	2.74	Rod	0.00	0.00	0.60	1.95	0.60	1.95	-0.35	-0.35	-1.16	-1.14	Wilcox ⁶
	8-Mar-97	1.23	Rod	1.51	2.64	0.20	0.65	0.50	1.66	1.16	1.16	3.80	3.82	UCB ⁸
SP-5	9-Dec-97	1.08	Rod	1.66	3.30	-0.19	-0.63	0.46	1.52	1.31	1.31	4.29	4.31	Siegel
	23-Feb-98	1.12	Rod	1.62	3.50	0.18	0.59	0.41	1.35	1.27	1.27	4.16	4.18	Siegel
	2-Dec-98	0.98	Rod	1.76	4.28	0.18	0.59	0.41	1.35	1.41	1.41	4.62	4.64	Siegel

**Appendix A. Sediment Pin Field Data and Calculations
Petaluma River Marsh, Sonoma County, California**

Location	Date	Distance Pin Top to Ground Surface		Thickness Deposited Sediment ¹	Time Since Baseline (yr)	Deposition Rate			Ground Surface Elevation ²			Data Source
		(m)	Method ⁵			Interval ³ (m/yr)	Interval ³ (ft/yr)	Cumulative ⁴ (ft/yr)	(m NAVD)	(ft MLLW)	(ft NAVD)	
SP-6	23-Feb-98	1.36	Rod		3.50							Stiegel
	25-Feb-98		Survey		3.51							Stiegel
	2-Dec-98	1.37	Rod	-0.01	4.28	-0.01	-0.04			0.61		Stiegel
SP-7	23-Feb-98	1.56	Rod		3.50							Stiegel
	10-Mar-98		Survey		3.55							Stiegel
	2-Dec-98	1.54	Rod	0.02	4.28	0.03	0.08			0.62		Stiegel
SP-8	23-Feb-98	1.23	Rod		3.50							Stiegel
	10-Mar-98		Survey		3.55							Stiegel
	2-Dec-98	1.15	Rod	0.08	4.28	0.10	0.34			0.55		Stiegel
SP-9	23-Feb-98	1.43	Rod		3.50							Stiegel
	10-Mar-98		Survey		3.55							Stiegel
	2-Dec-98	1.30	Rod	0.13	4.28	0.17	0.55			0.36		Stiegel
SP-10	23-Feb-98	1.69	Rod		3.50							Stiegel
	25-Feb-98		Survey		3.51							Stiegel
	2-Dec-98	1.74	Rod	-0.05	4.28	-0.08	-0.21			0.53		Stiegel
SP-11	23-Feb-98	1.50	Rod		3.50							Stiegel
	25-Feb-98		Survey		3.51							Stiegel
	2-Dec-98	1.46	Rod	0.04	4.28	0.05	0.17			0.76		Stiegel
SP-12	23-Feb-98	1.71	Rod		3.50							Stiegel
	25-Feb-98		Survey		3.51							Stiegel
	2-Dec-98	1.72	Rod	-0.01	4.28	-0.01	-0.04			0.69		Stiegel
SP-13	23-Feb-98	1.86	Rod		3.50							Stiegel
	25-Feb-98		Survey		3.51							Stiegel
	2-Dec-98	1.86	Rod	-0.01	4.28	-0.01	-0.04			0.62		Stiegel
SP-14	23-Feb-98	1.46	Rod		3.50							Stiegel
	25-Feb-98		Survey		3.51							Stiegel
	2-Dec-98	1.47	Rod	-0.01	4.28	-0.01	-0.04			0.32		Stiegel
SP-15	23-Feb-98	1.43	Rod		3.50							Stiegel
	25-Feb-98		Survey		3.51							Stiegel
	2-Dec-98	1.28	Rod	0.15	4.28	0.19	0.64			0.68		Stiegel

**Appendix A. Sediment Pin Field Data and Calculations
Petaluma River Marsh, Sonoma County, California**

Location	Date	Distance Pin Top to Ground Surface		Thickness Deposited Sediment ¹ (m)	Time Since Baseline (yr)	Deposition Rate			Ground Surface Elevation ²			Data Source		
		Method ⁵	(m)			Interval ³ (m/yr)	(m/yr)	(ft/yr)	Cumulative ⁴ (m/yr)	(m MLLW)	(m NAVD)		(ft MLLW)	(ft NAVD)
SP-16	23-Feb-98	Rod	1.62	0.02	3.50								Stapel	
	25-Feb-98	Survey			3.51								Stapel	
	2-Dec-98	Rod	1.60	0.02	4.28	0.03	0.08		0.60				Stapel	
SP-17	23-Feb-98	Rod	2.38		3.50								Stapel	
	25-Feb-98	Survey			3.51								Stapel	
	2-Dec-98	Rod	2.41	-0.03	4.28	-0.04	-0.13		0.33				Stapel	
SP-18	23-Feb-98	Rod	1.25		3.50								Stapel	
	25-Feb-98	Survey			3.51								Stapel	
	2-Dec-98	Rod	1.21	0.04	4.28	0.05	0.17		0.59				Stapel	
SP-19	23-Feb-98	Rod	na		3.50								Stapel	
	10-Mar-98	Survey	1.30	-0.09	3.55								Stapel	
	2-Dec-98	Rod	1.39		4.28	-0.12	-0.40		0.37				Stapel	
Statistics for SP-1 to SP-5 (Full CDFG) and Full CDFG Excluding SP-5 (located within a channel)														
Mean -- Full CDFG Data Set														
(n=4)	24-Aug-94			0.00	0.00	0.59	1.92	0.59	1.92	0.69	1.92	0.37	1.20	
(n=3)	14-Nov-96			1.31	2.23	0.37	1.21	0.37	1.21	0.54	1.78	1.29	1.46	
(n=5)	8-Mar-97			1.38	2.54	0.12	0.40	0.12	0.40	0.45	1.46	1.39	1.41	
(n=5)	12-Dec-97			1.47	3.30	0.16	0.53	0.16	0.53	0.43	1.41	1.41	1.41	
(n=5)	23-Feb-98			1.50	3.50	0.08	0.27	0.08	0.27	0.37	1.20	1.42	1.42	
(n=5)	2-Dec-98			1.57	4.28	0.06	0.19	0.06	0.19	0.36	1.17	1.51	1.52	
Mean -- Full CDFG Excluding SP-5														
(n=3)	24-Aug-94			0.00	0.00	0.59	1.92	0.59	1.92	0.69	1.92	0.37	1.20	
(n=3)	14-Nov-96			1.31	2.23	0.31	1.02	0.31	1.02	0.53	1.74	1.34	1.41	
(n=4)	8-Mar-97			1.34	2.54	0.10	0.34	0.10	0.34	0.43	1.41	1.42	1.41	
(n=4)	12-Dec-97			1.42	3.30	0.25	0.82	0.25	0.82	0.42	1.38	1.46	1.47	
(n=4)	23-Feb-98			1.47	3.50	0.06	0.19	0.06	0.19	0.36	1.17	1.52	1.52	
(n=4)	2-Dec-98			1.52	4.28	0.06	0.19	0.06	0.19	0.36	1.17	1.52	1.52	

**Appendix A. Sediment Pin Field Data and Calculations
Petaluma River Marsh, Sonoma County, California**

Location	Date	Distance Pin Top to Ground Surface		Thickness Deposited Sediment ¹	Time Since Baseline (yr)	Deposition Rate			Ground Surface Elevation ²		Data Source	
		(m)	Method ⁵			Interval ³ (m/yr)	Cumulative ⁴ (ft/yr)	(m MLLW)	(ft NAVD)			
Standard Deviation -- Full CDFG Data Set												
(n=4)	24-Aug-94			na	0.00	0.03	0.11	0.03	0.11	0.18	0.58	
(n=3)	14-Nov-96			0.07	2.23	0.03	0.11	0.03	0.11	0.03	0.11	
(n=6)	8-Mar-97			0.11	2.54	0.19	0.62	0.04	0.14	0.11	0.36	
(n=6)	12-Dec-97			0.13	3.30	0.04	0.14	0.04	0.13	0.09	0.28	
(n=6)	23-Feb-98			0.10	3.50	0.25	0.81	0.03	0.09	0.10	0.34	
(n=5)	2-Dec-98			0.14	4.28	0.06	0.21	0.03	0.10	0.07	0.25	
Standard Deviation -- Full CDFG Excluding SP-5												
(n=3)	24-Aug-94			na	0.00	0.03	0.11	0.03	0.11	0.10	0.34	
(n=3)	14-Nov-96			0.07	2.23	0.03	0.11	0.03	0.11	0.03	0.11	
(n=4)	8-Mar-97			0.09	2.54	0.16	0.52	0.03	0.11	0.06	0.20	
(n=4)	12-Dec-97			0.09	3.30	0.02	0.05	0.03	0.09	0.07	0.21	
(n=4)	23-Feb-98			0.09	3.50	0.17	0.57	0.02	0.08	0.04	0.19	
(n=4)	2-Dec-98			0.09	4.28	0.04	0.12	0.02	0.07	0.05	0.17	
Coefficient of Variation -- Full Data Set												
(n=3)	14-Nov-96			5.6%	2.23	5.6%	5.6%		5.6%			
(n=5)	8-Mar-97			7.7%	2.54	50.9%	7.7%		7.7%			
(n=5)	12-Dec-97			8.1%	3.30	35.6%	9.2%		9.2%			
(n=5)	23-Feb-98			6.6%	3.50	153.6%	6.6%		6.6%			
(n=5)	2-Dec-98			8.6%	4.28	77.0%	8.6%		8.6%			
Coefficient of Variation -- Excluding SP-5												
(n=3)	14-Nov-96			5.6%	2.23	5.6%	5.6%		5.6%			
(n=4)	8-Mar-97			6.4%	2.54	51.2%	6.4%		6.4%			
(n=4)	12-Dec-97			6.5%	3.30	14.4%	6.5%		6.5%			
(n=4)	23-Feb-98			5.8%	3.50	69.3%	5.8%		5.8%			
(n=18)	2-Dec-98			6.1%	4.28	64.2%	6.1%		6.1%			

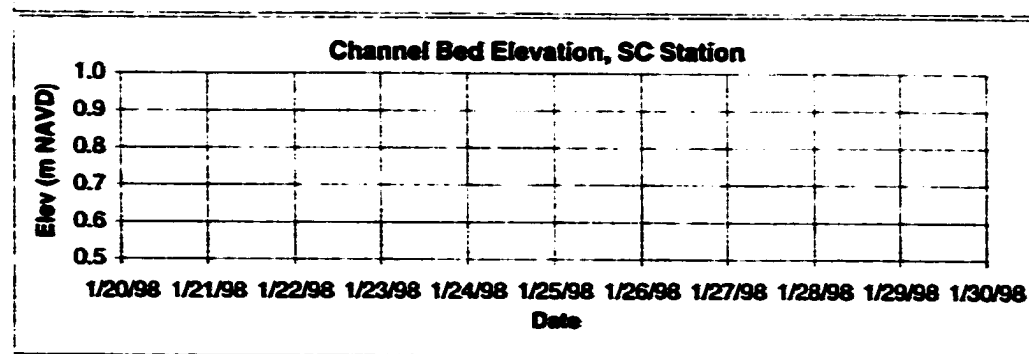
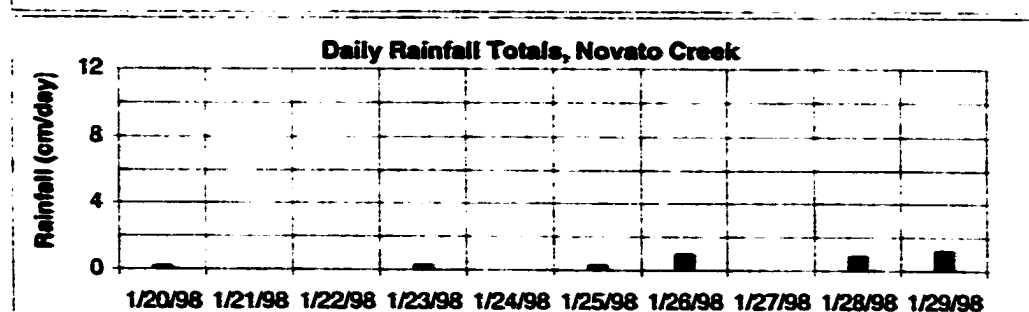
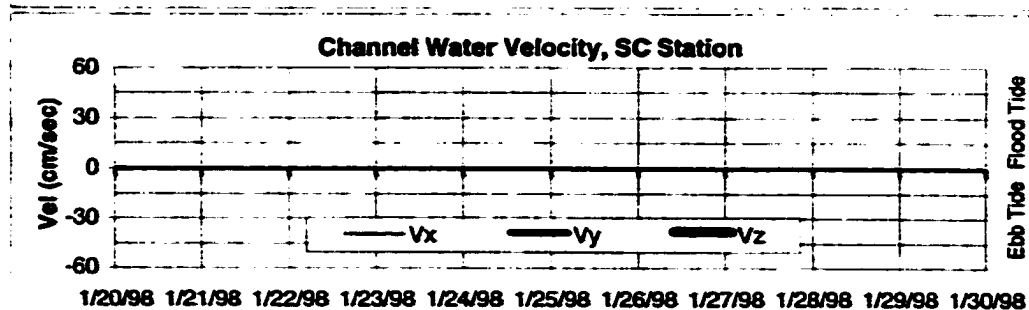
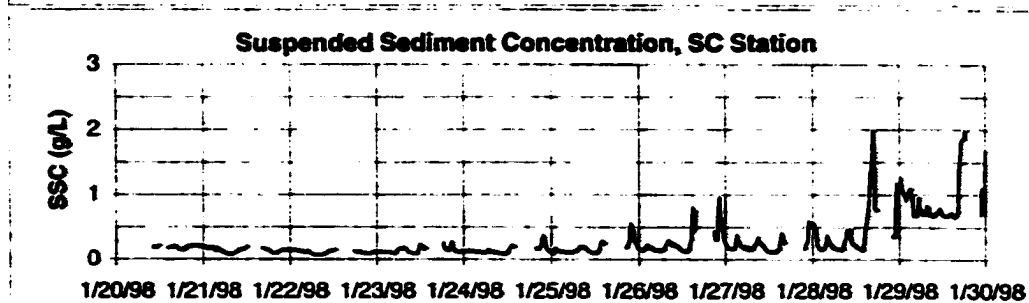
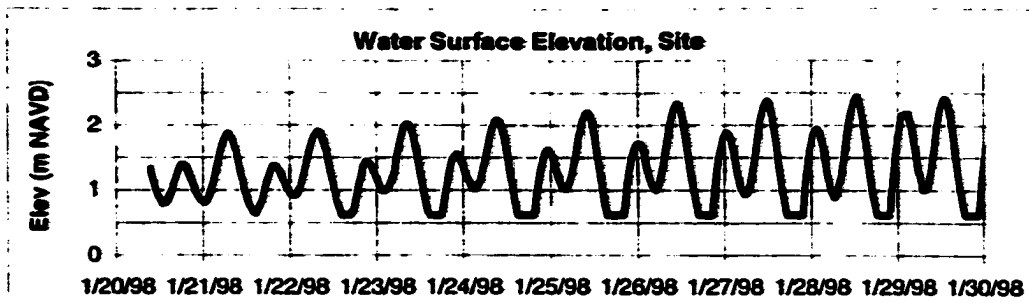
Appendix A. Sediment Pin Field Data and Calculations Petaluma River Marsh, Sonoma County, California

Notes:

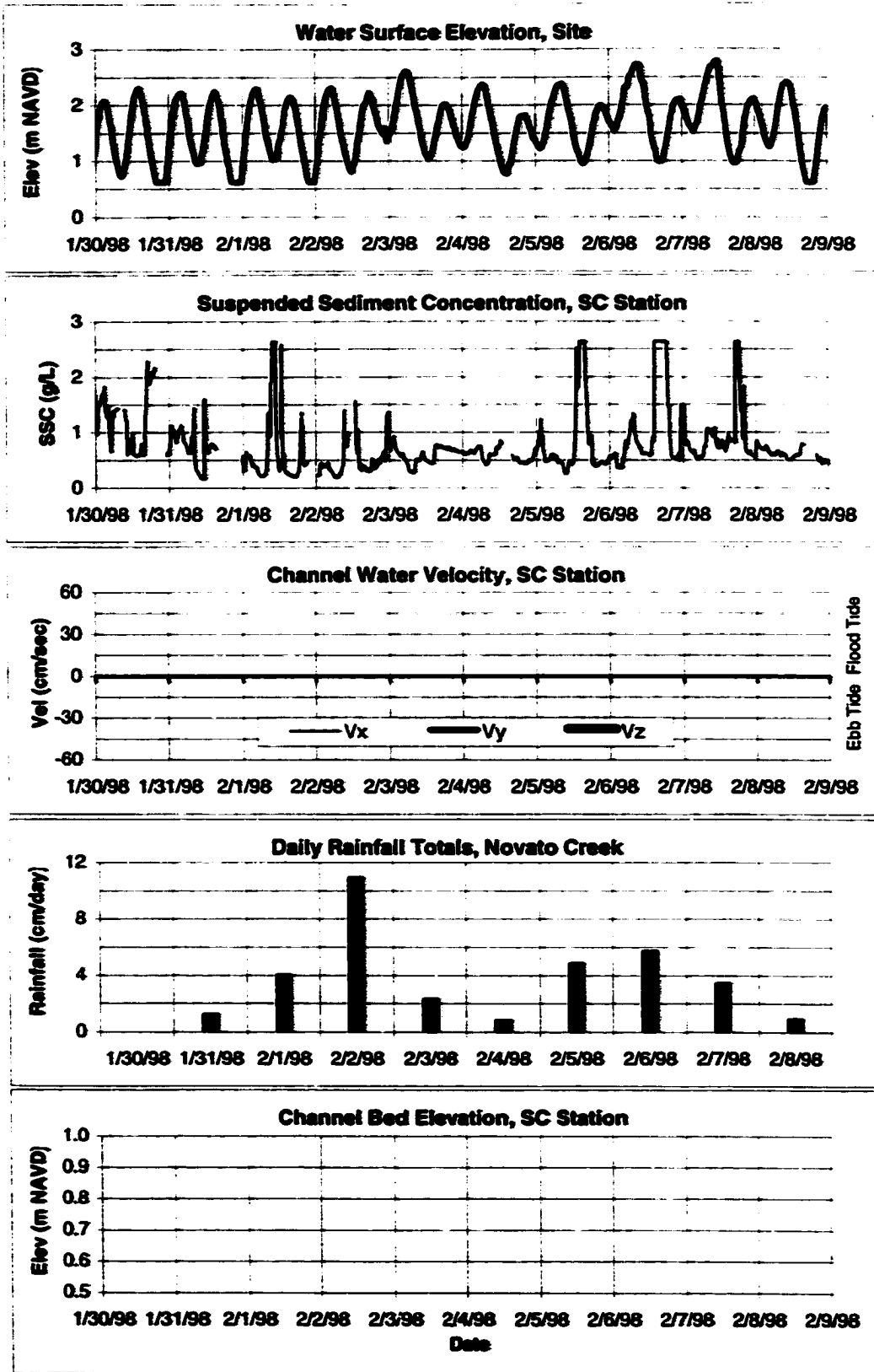
1. Thickness represents total deposition since levee breach.
2. Elevations determined from 25-Feb-98 and 10-Mar-98 topographic surveys; elevations for earlier dates back calculated.
3. Interval measures deposition rate since previous sampling event.
4. Cumulative measures deposition rate since levee breach.
5. Rod method = graduated stadia rod placed on ground at pin base; height of pin top read from rod, using small (20 cm²) rod base; +/- 3 cm.
Survey method = topographic survey of pin top and ground surface elevations, using large rod base (700 cm²); +/- 1 cm.
6. Baseline data collected by Carl Wilcox, CDFG.
7. 1986 data collected by Kathy Web, CDFG.
8. Spring 1997 data collected by UCB Geography field class.
9. Coefficient of variation = (st dev / mean) * 100, and allows comparison of variability when have differences in mean values.

Appendix B

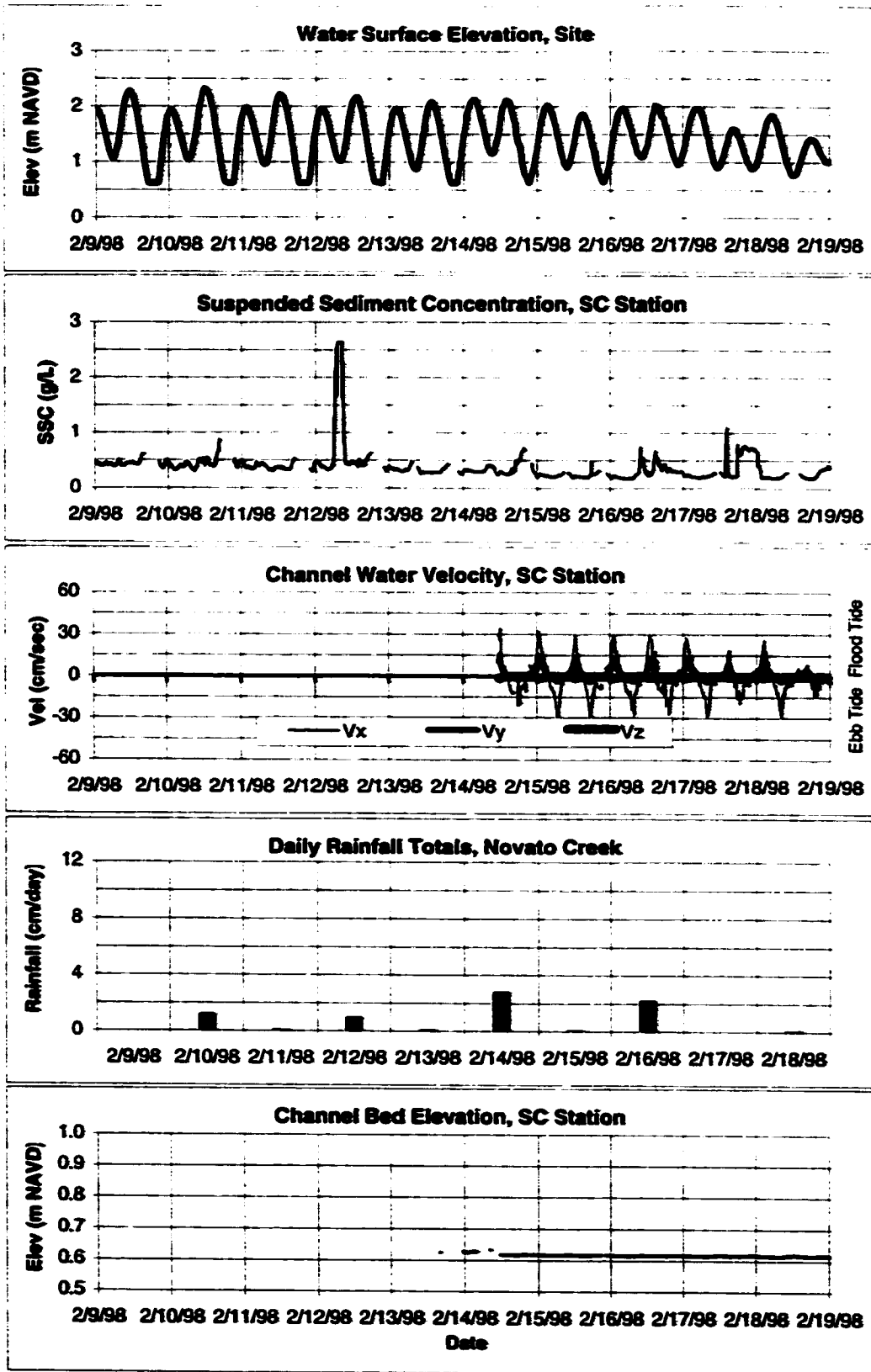
Times Series Water Column Physical Data



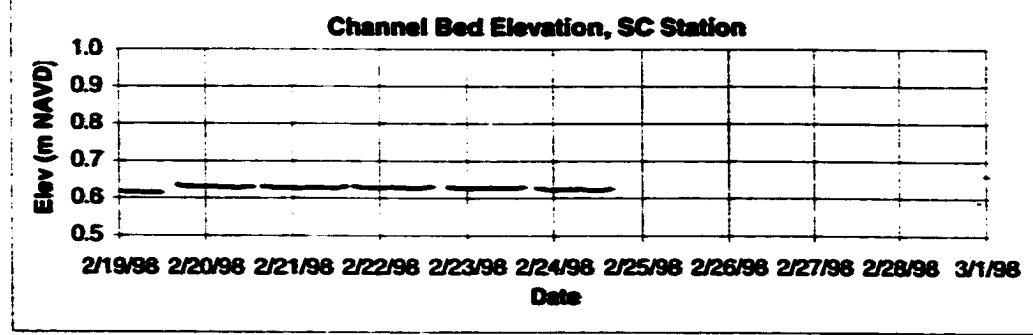
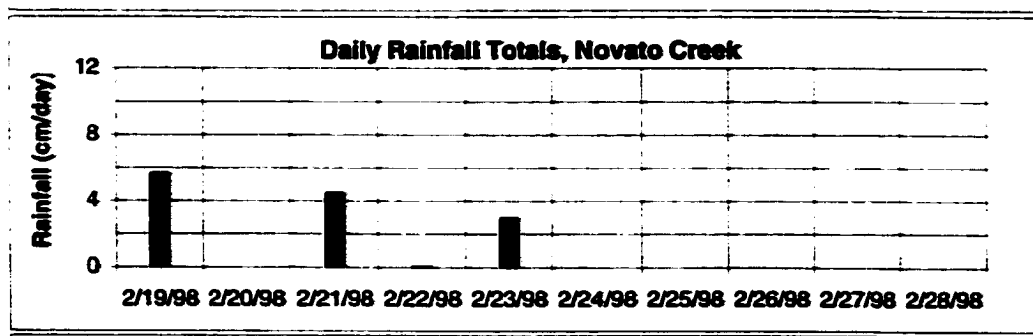
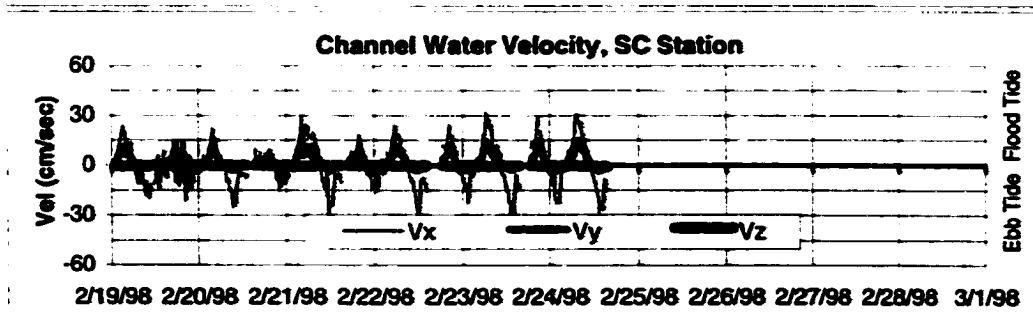
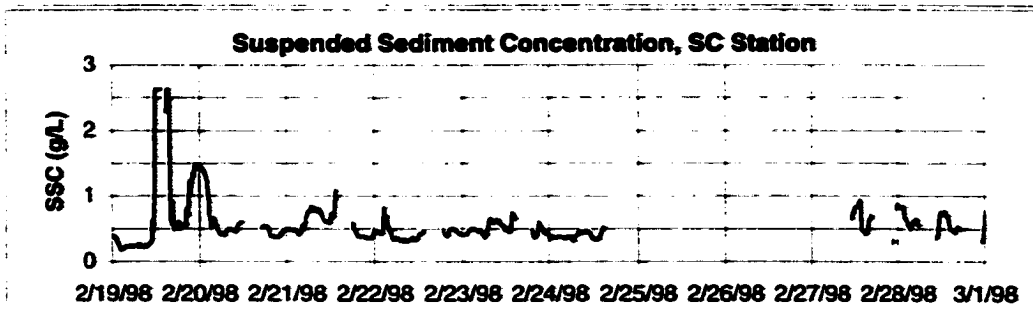
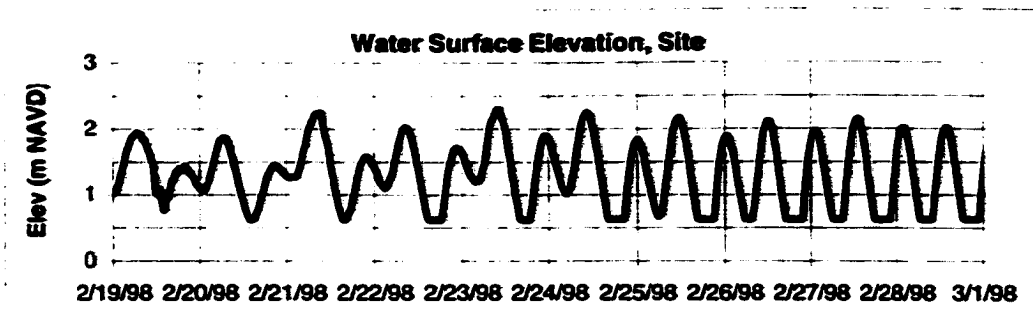
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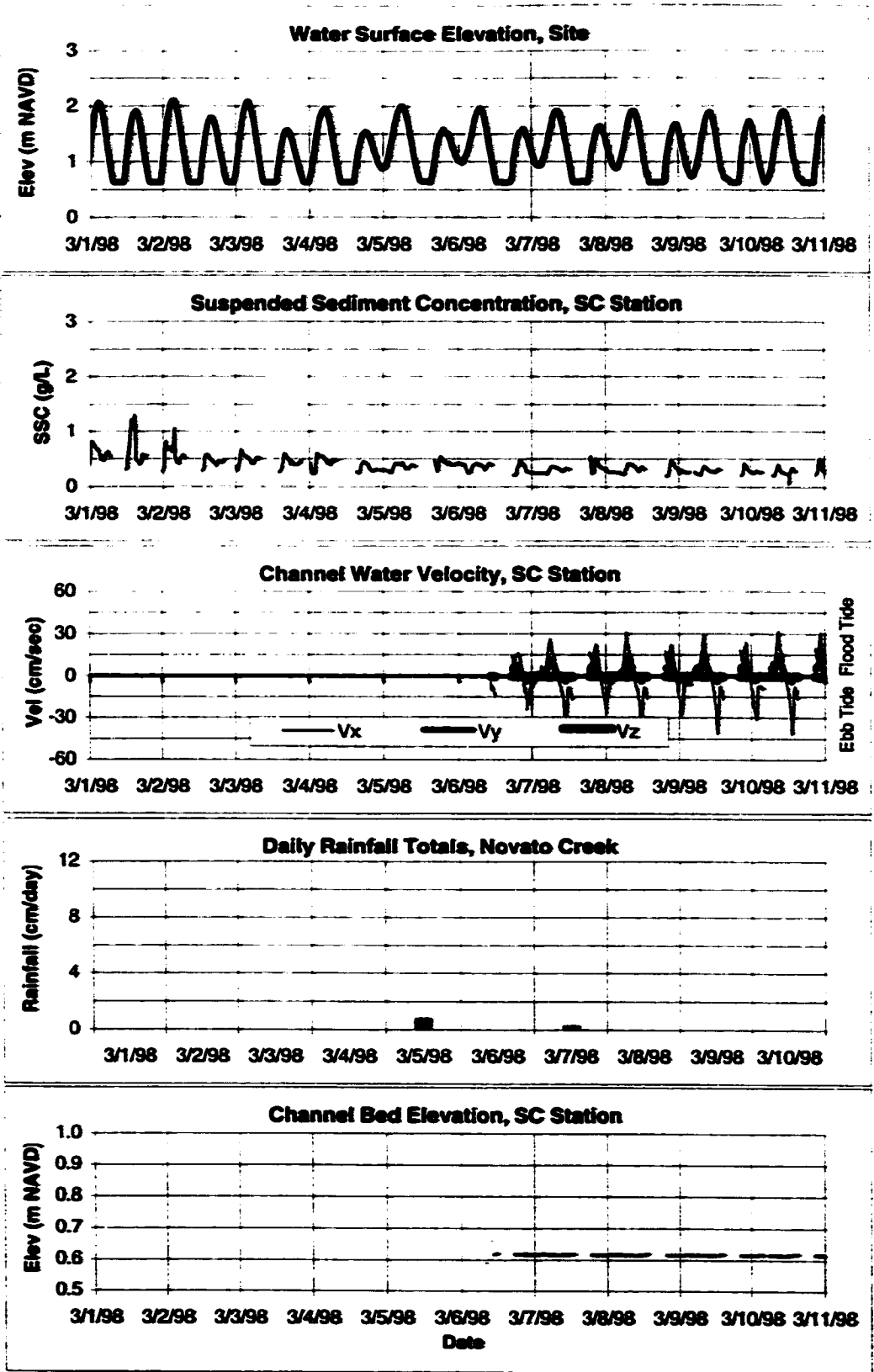
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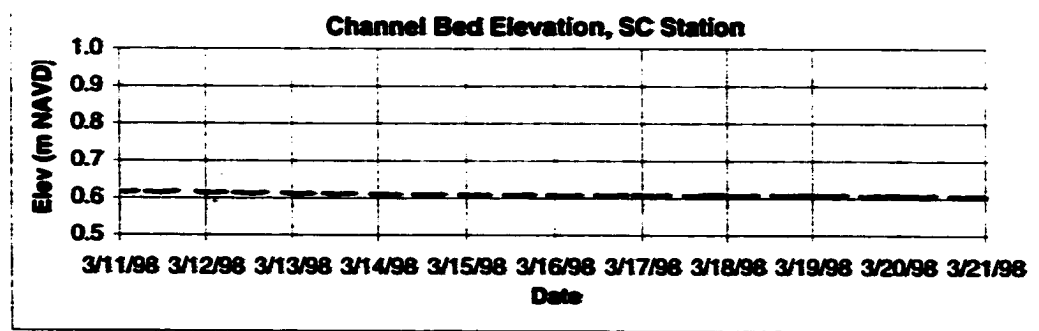
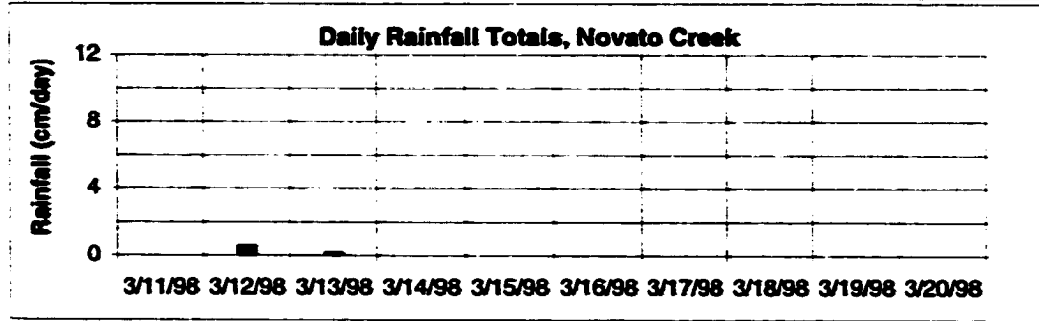
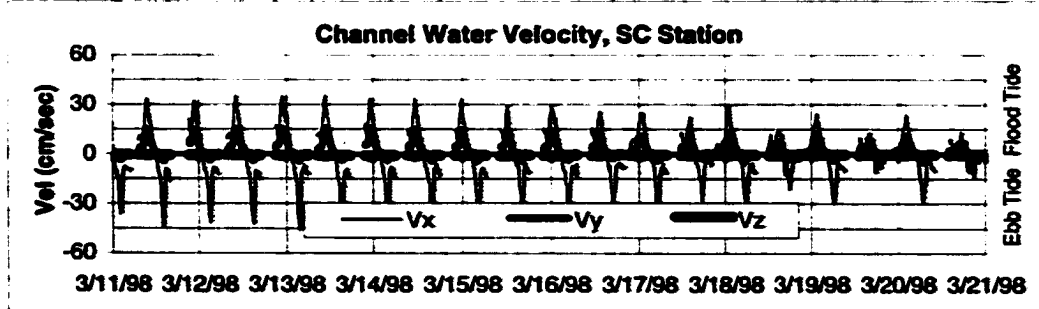
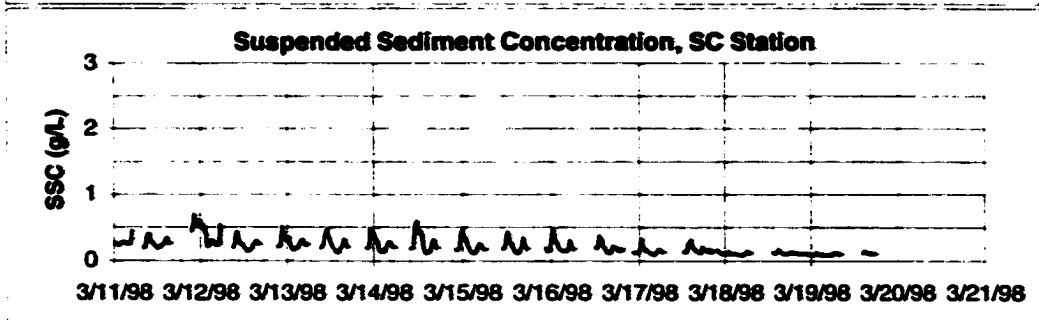
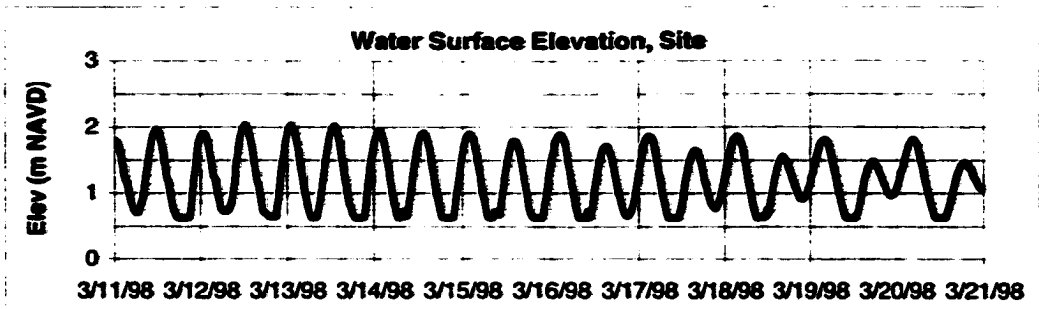
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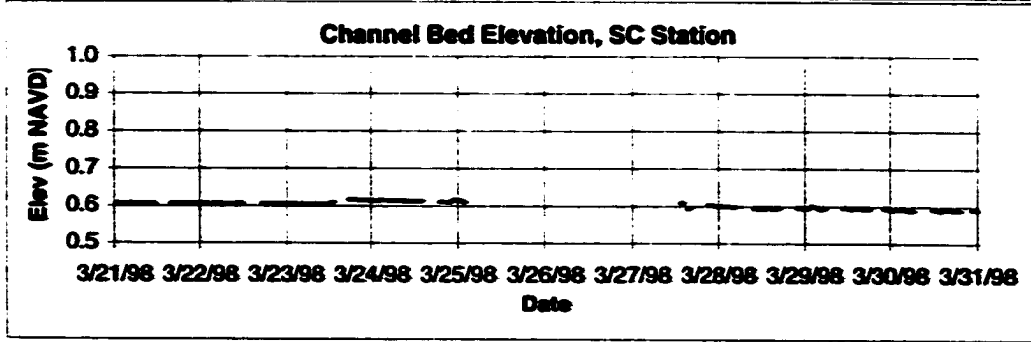
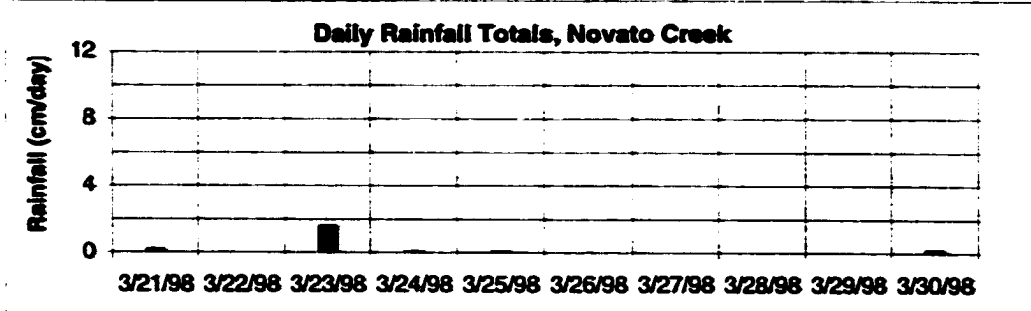
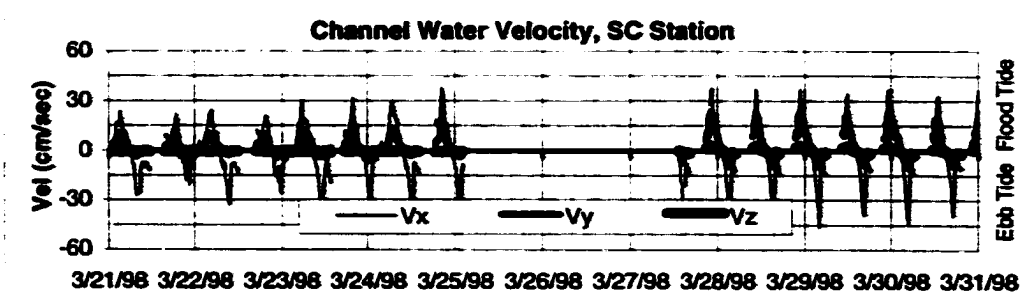
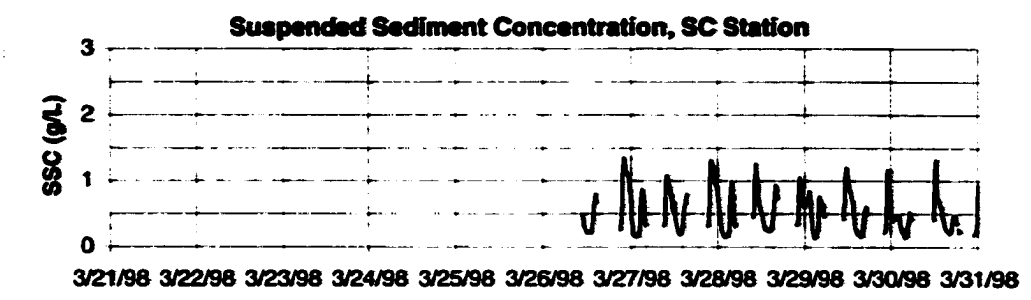
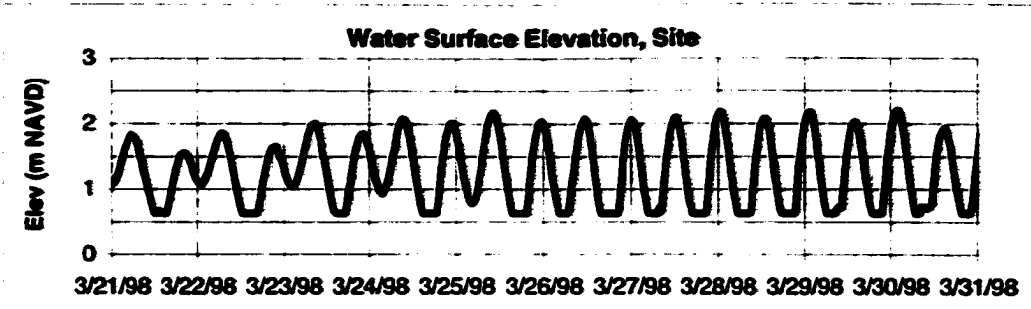
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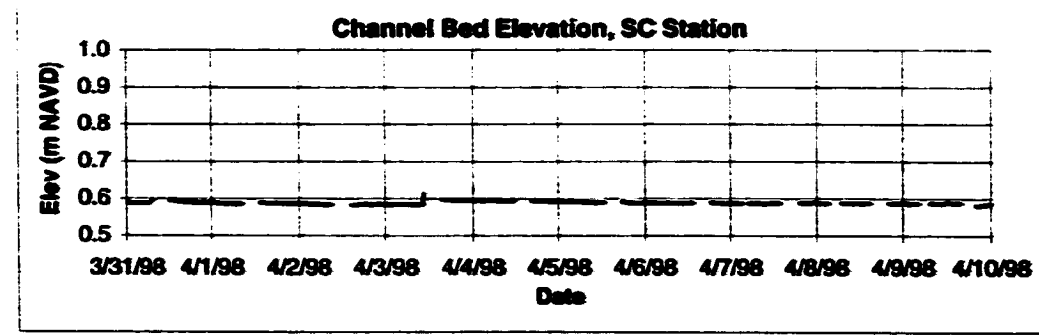
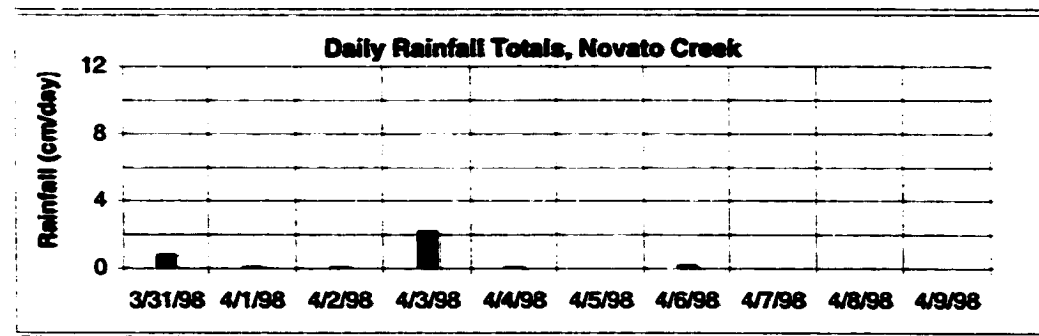
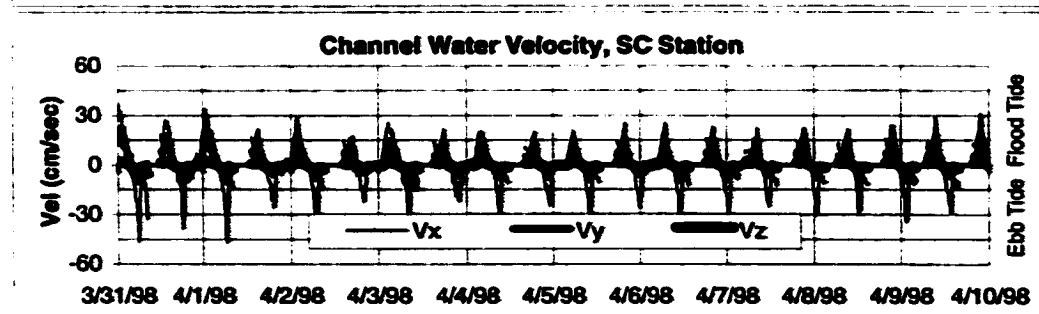
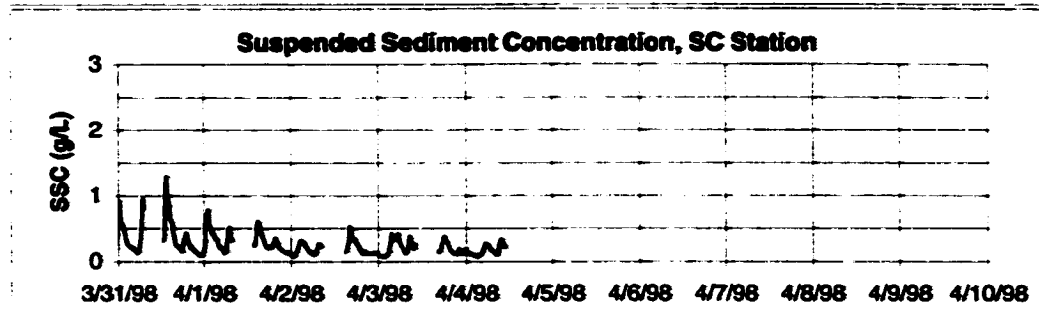
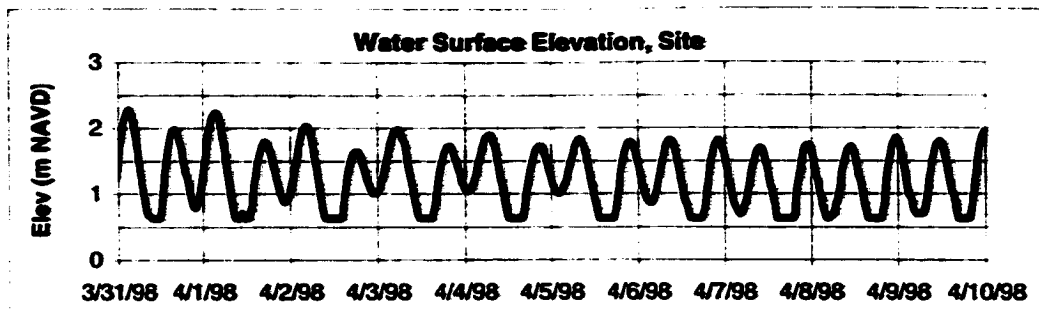
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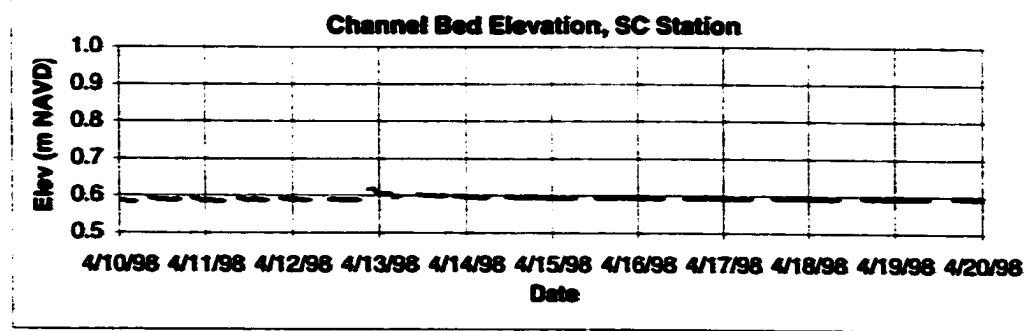
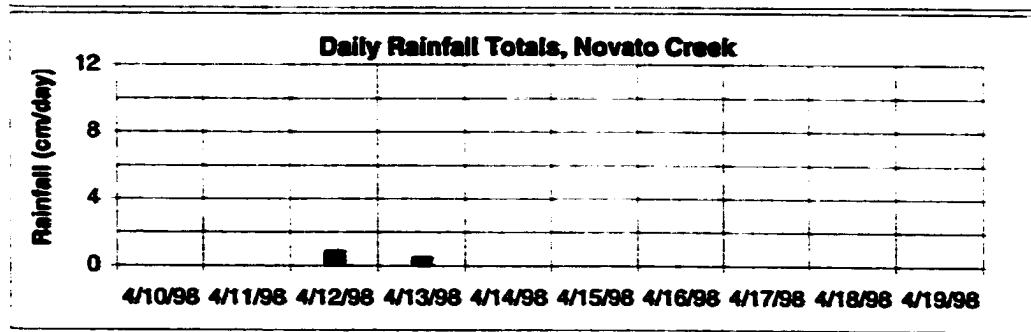
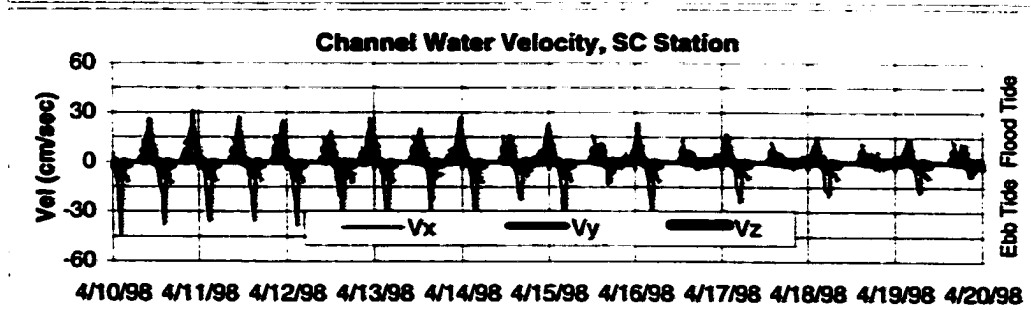
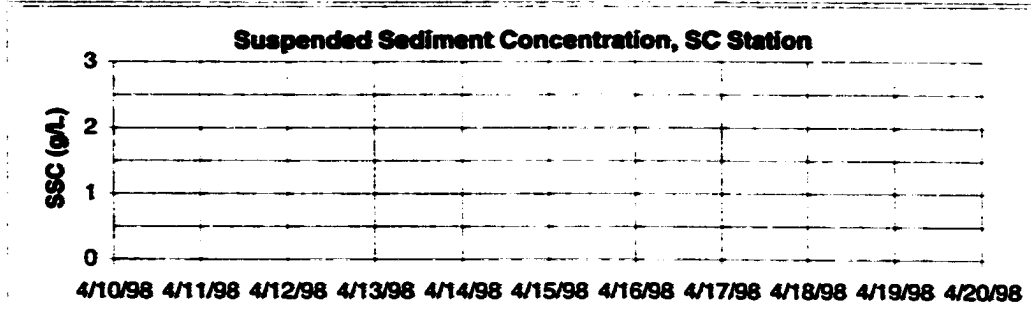
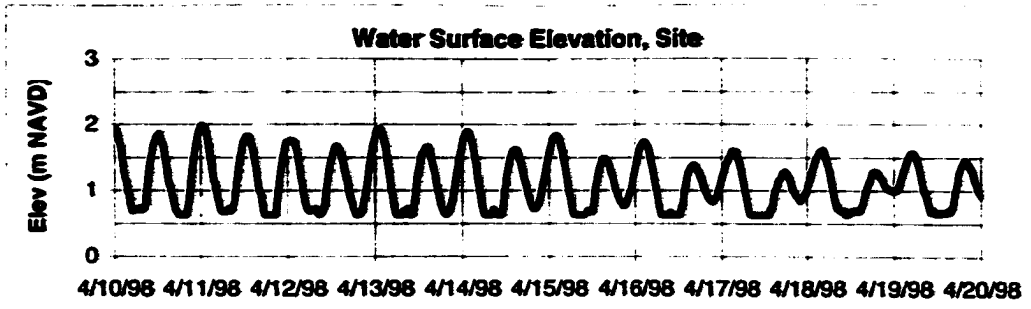
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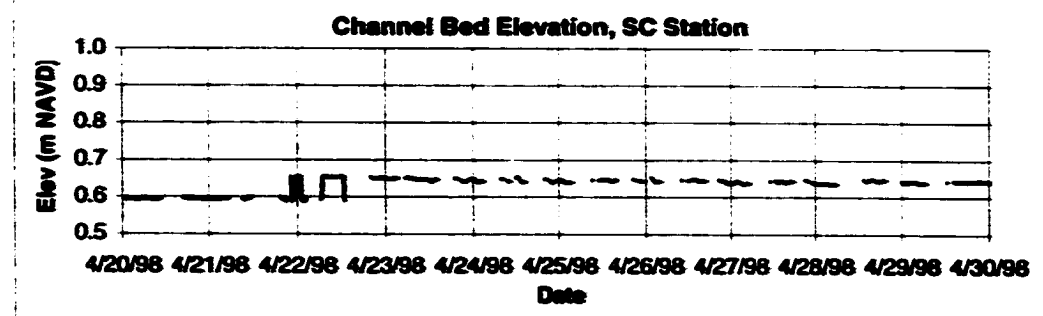
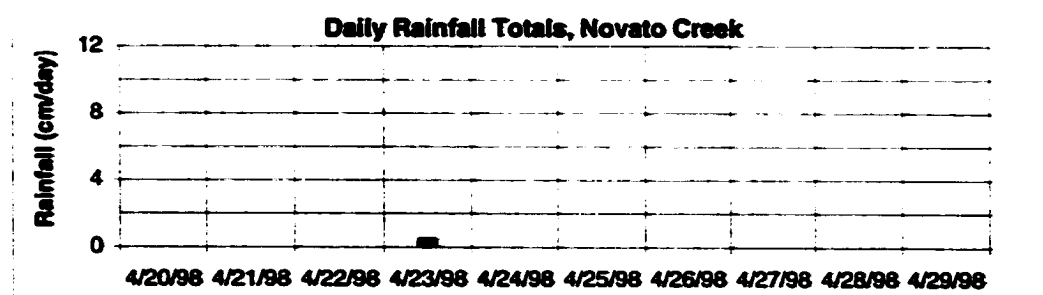
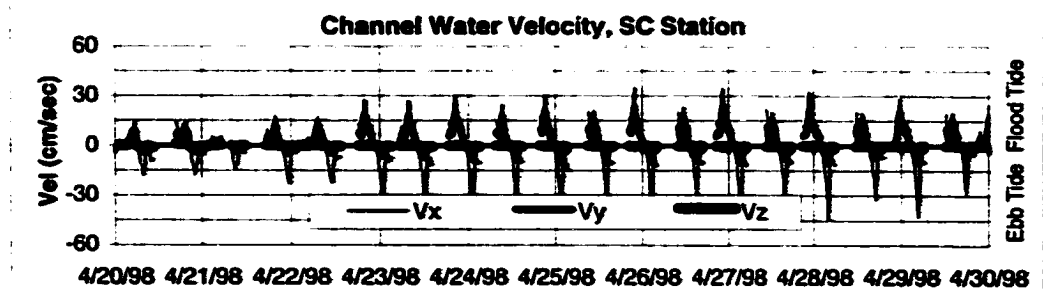
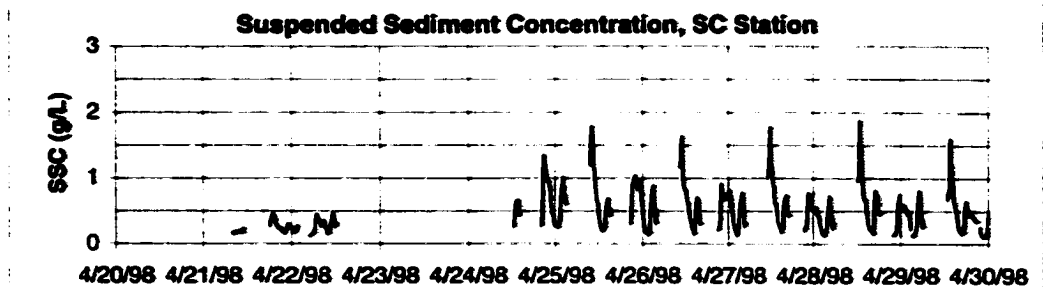
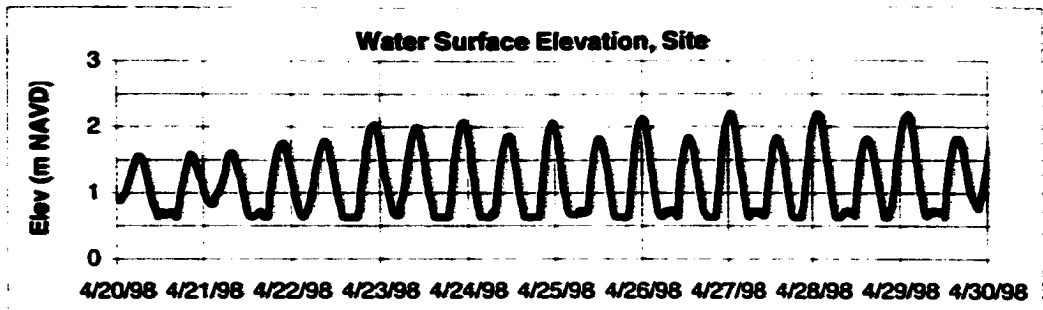
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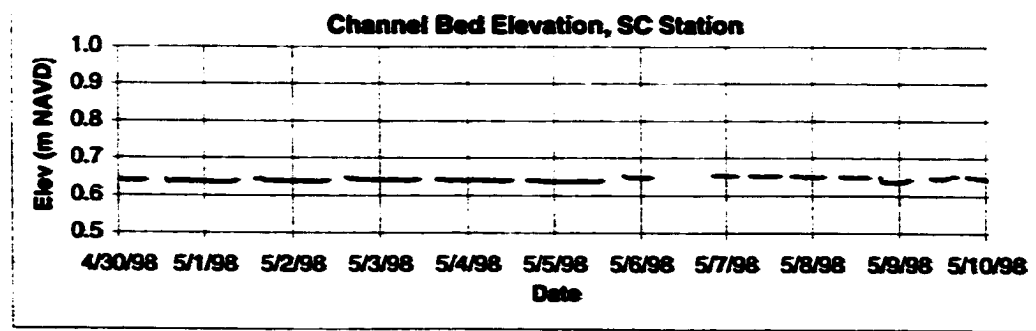
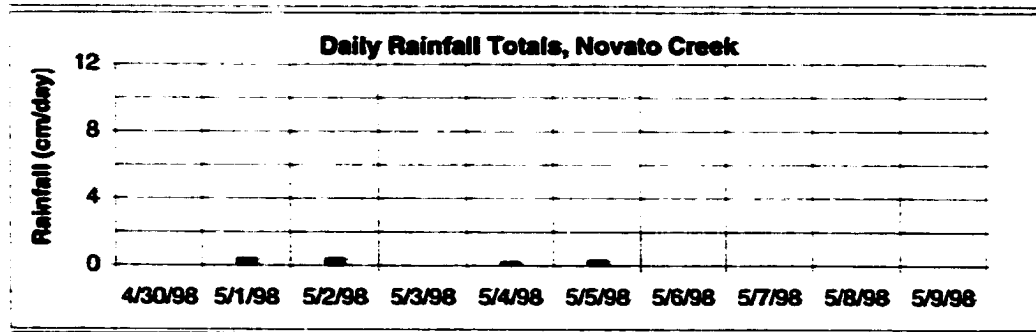
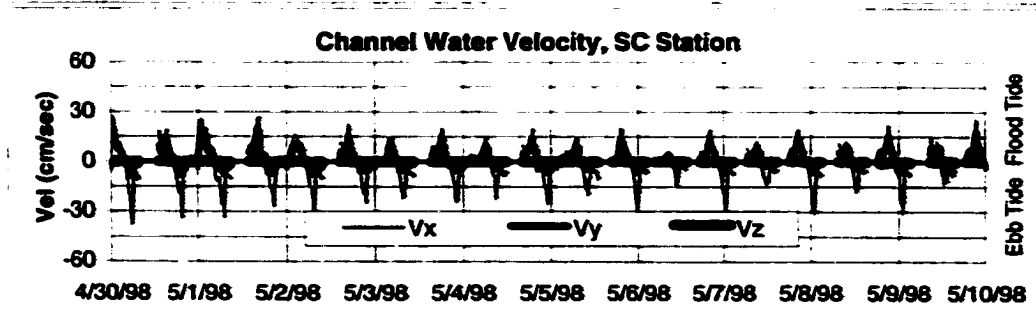
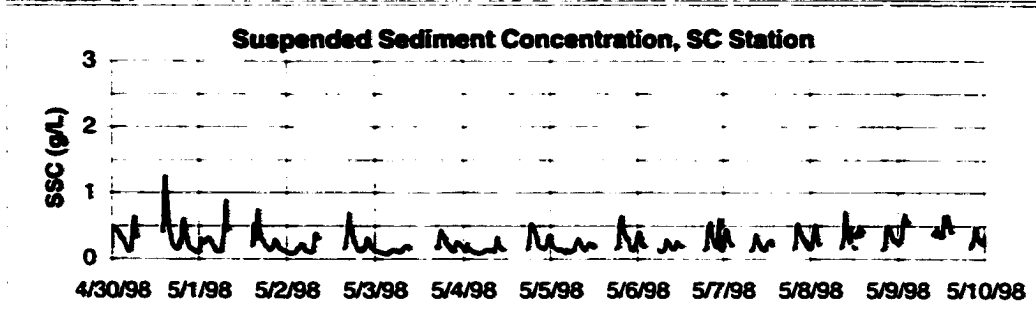
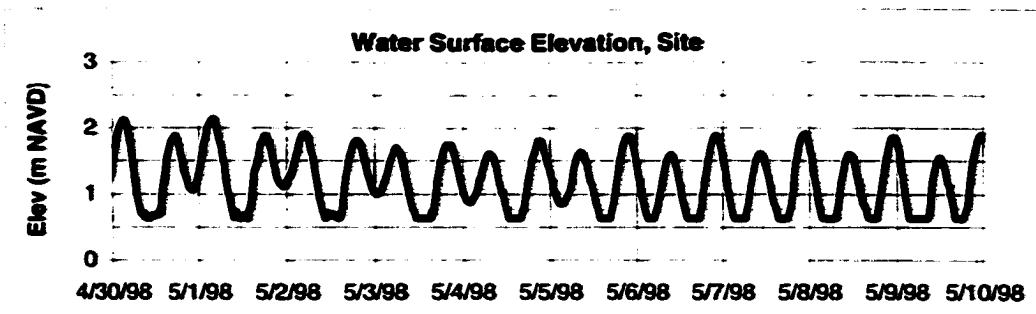
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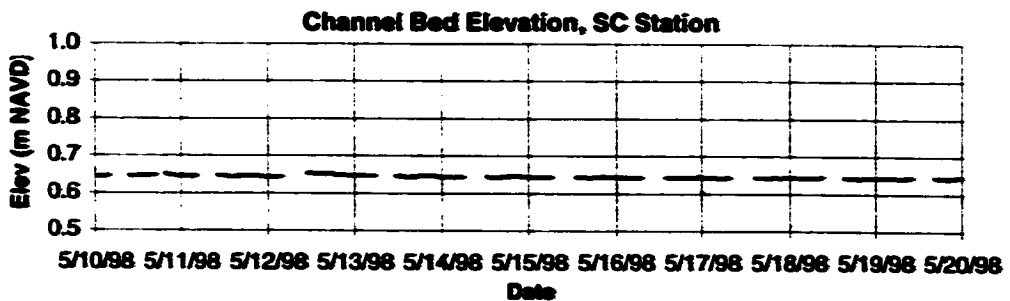
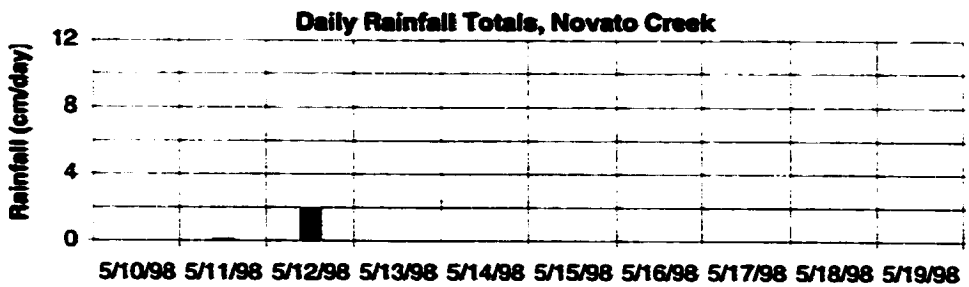
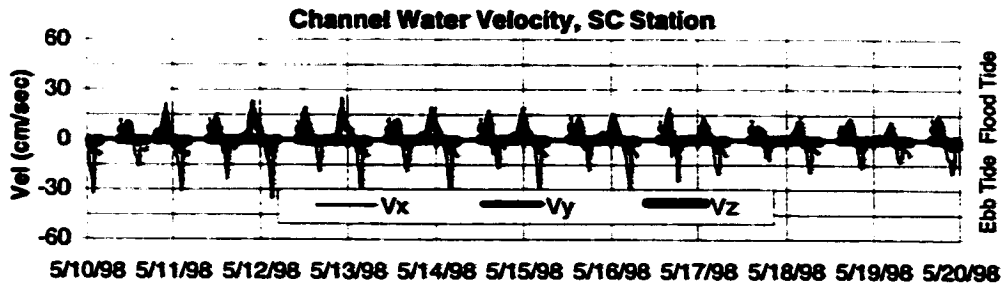
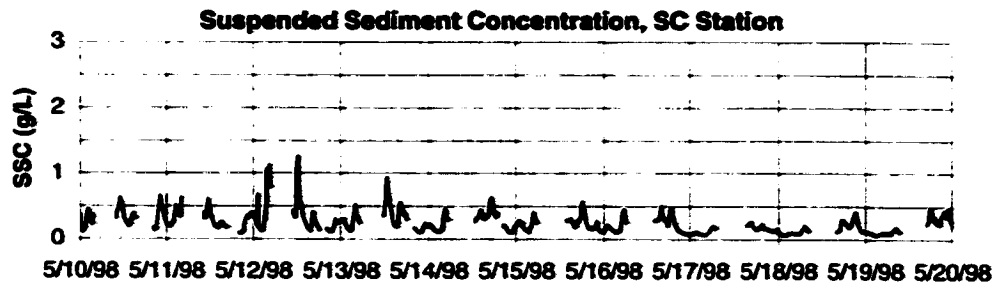
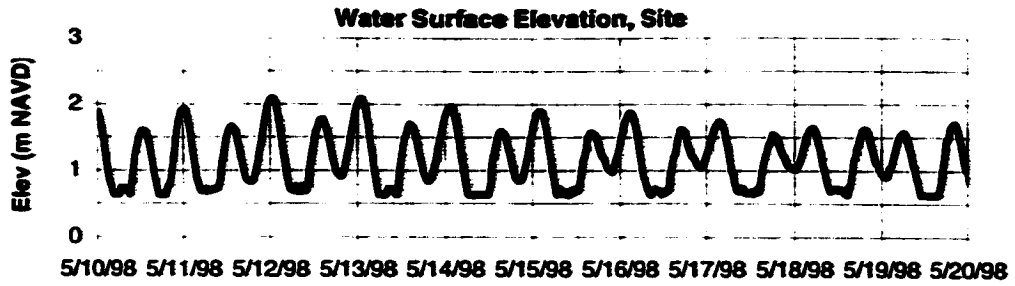
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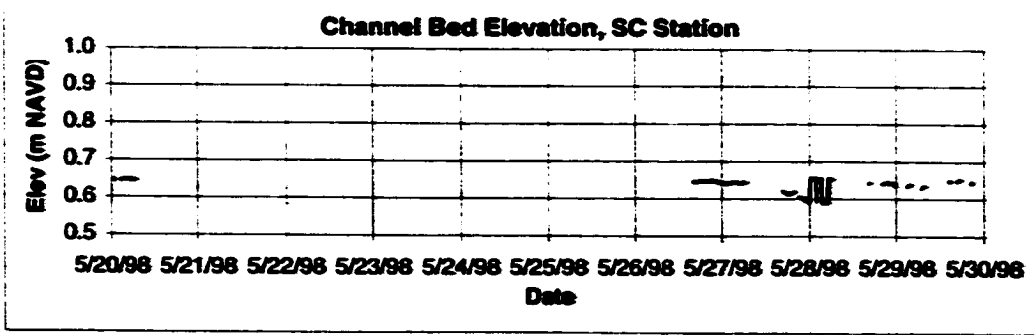
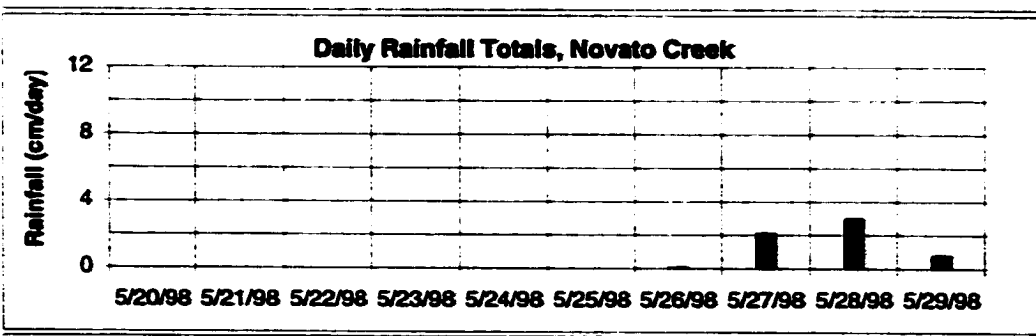
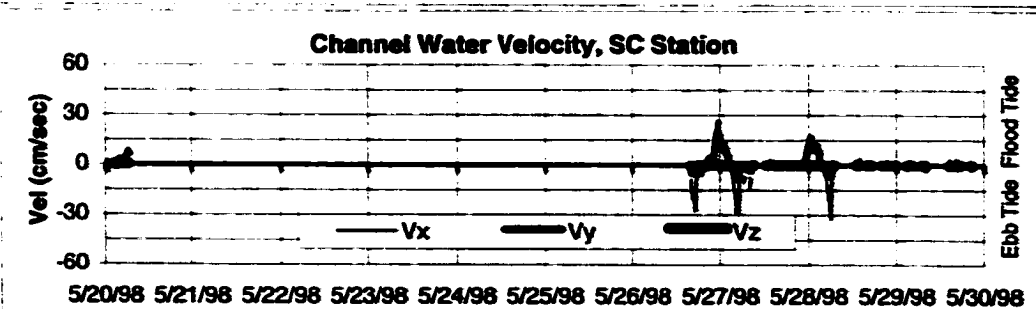
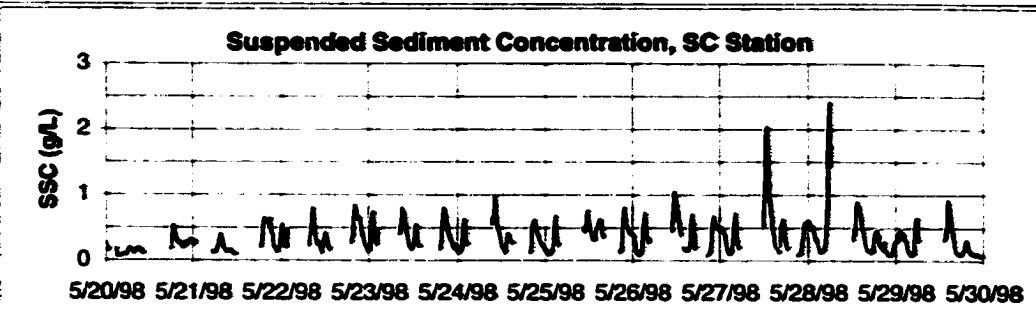
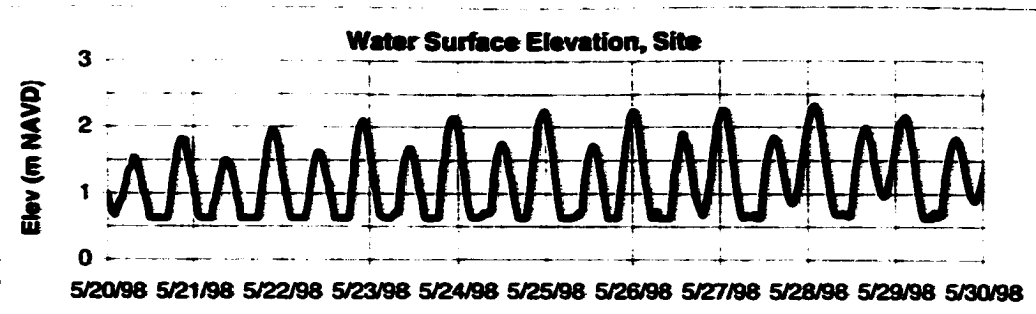


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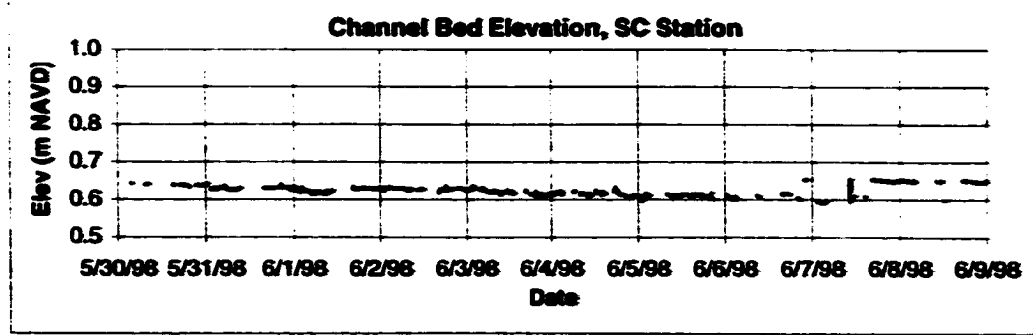
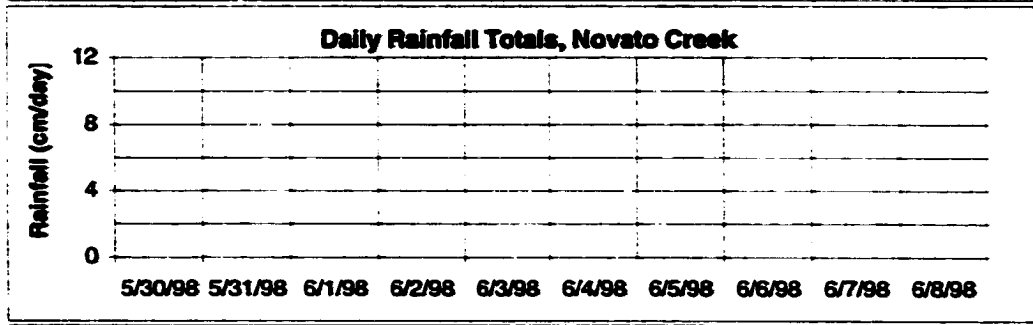
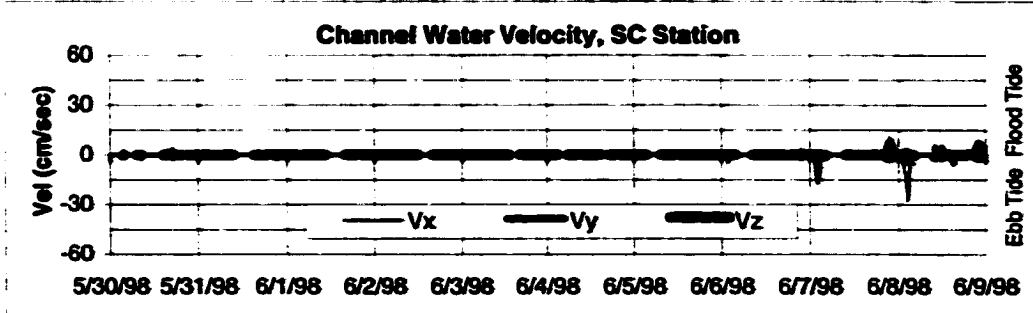
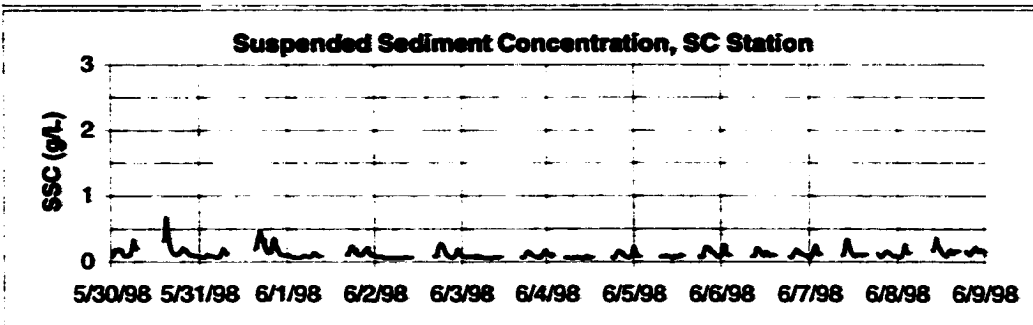
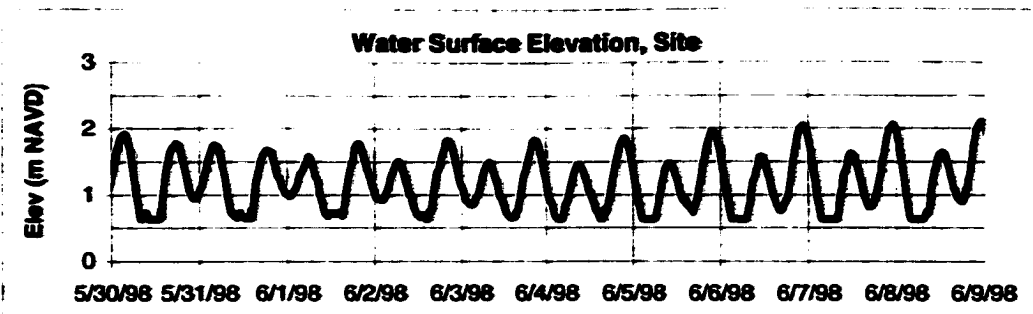


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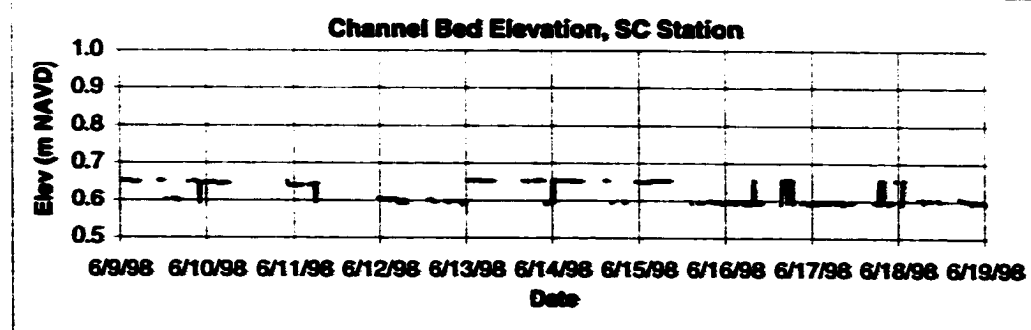
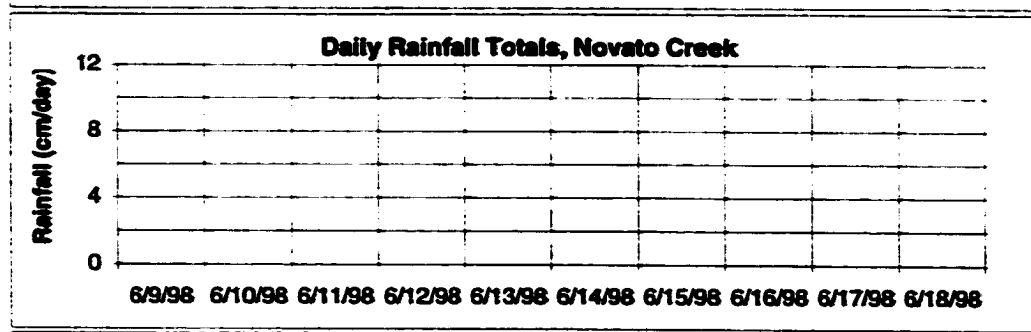
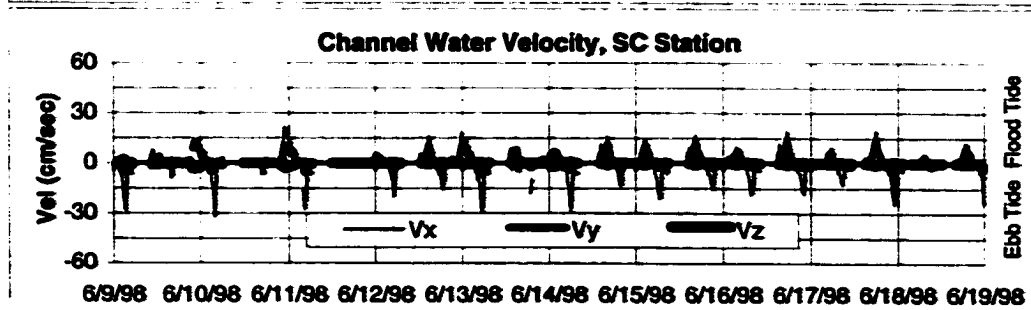
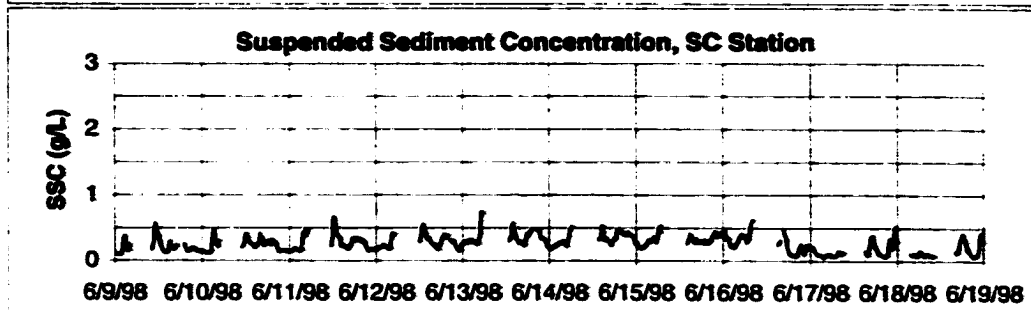
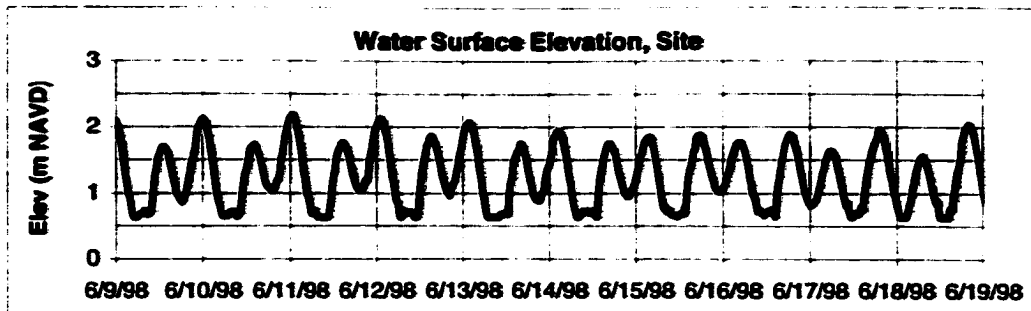




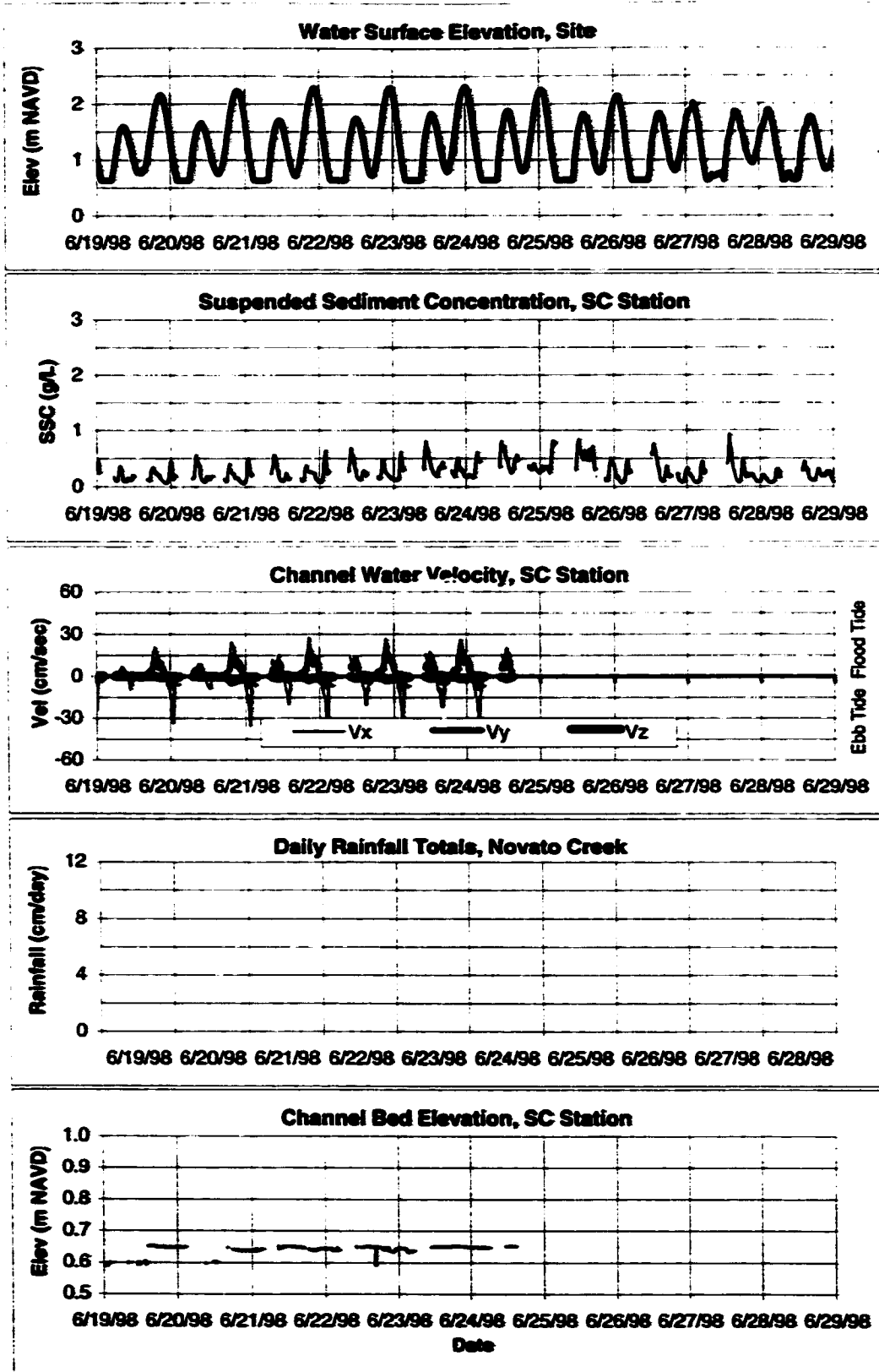
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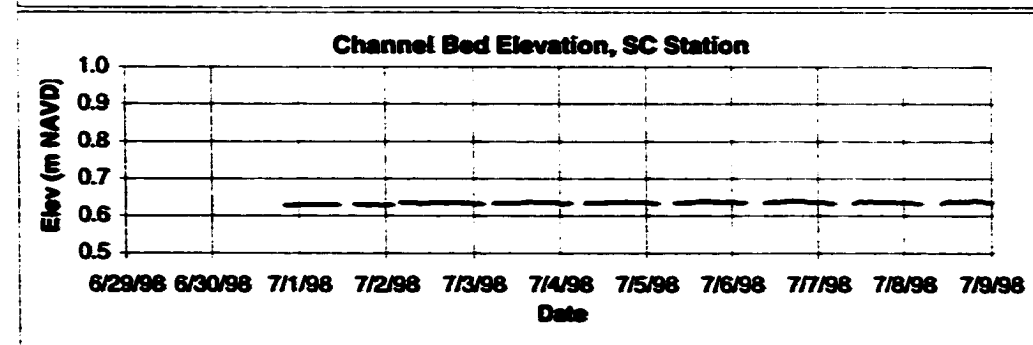
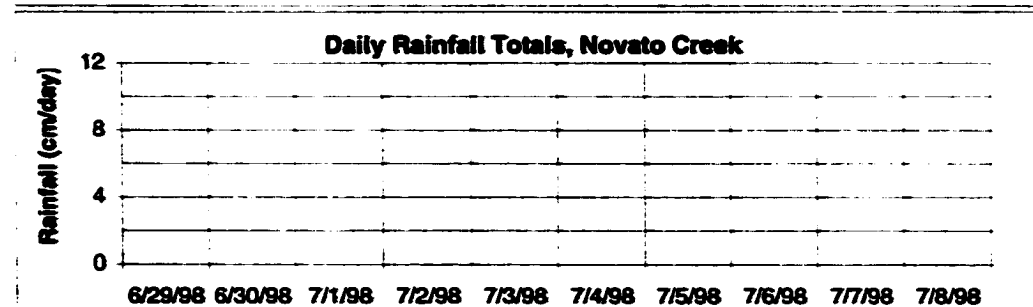
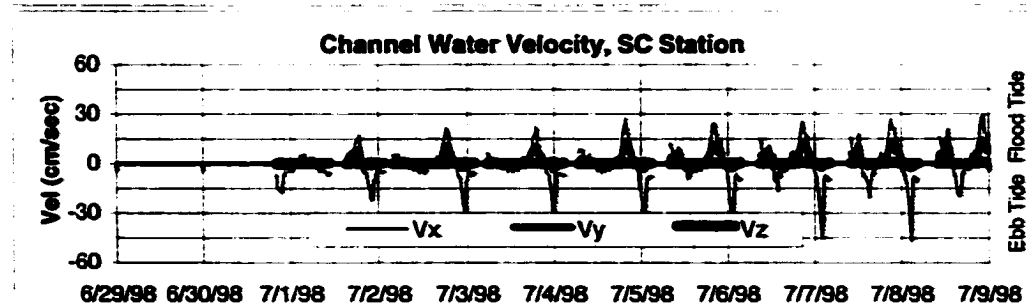
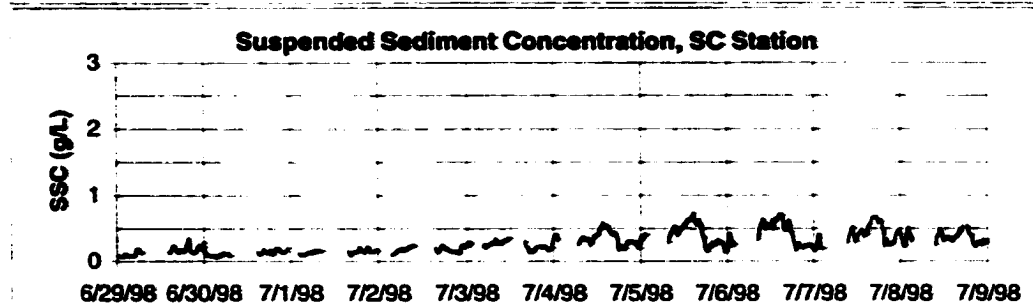
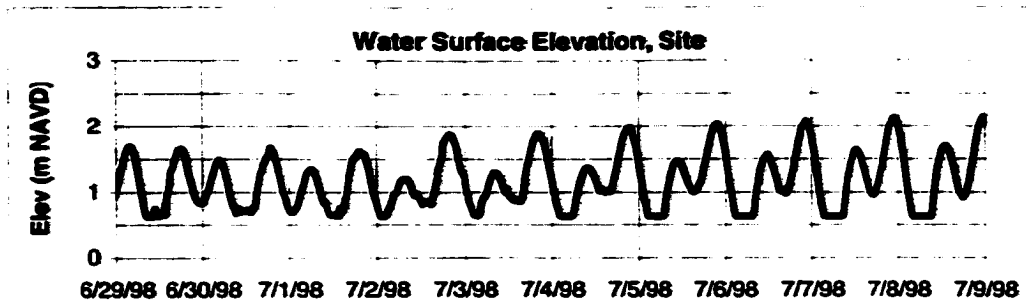
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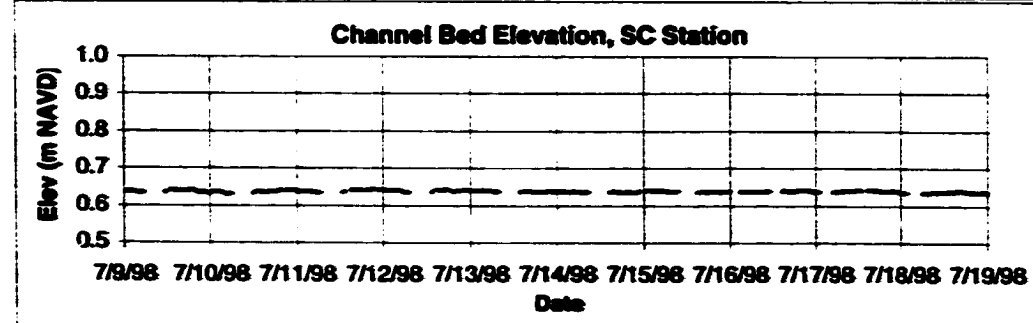
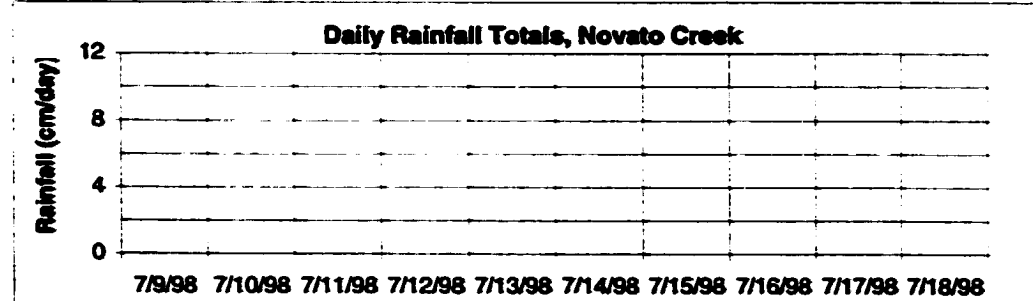
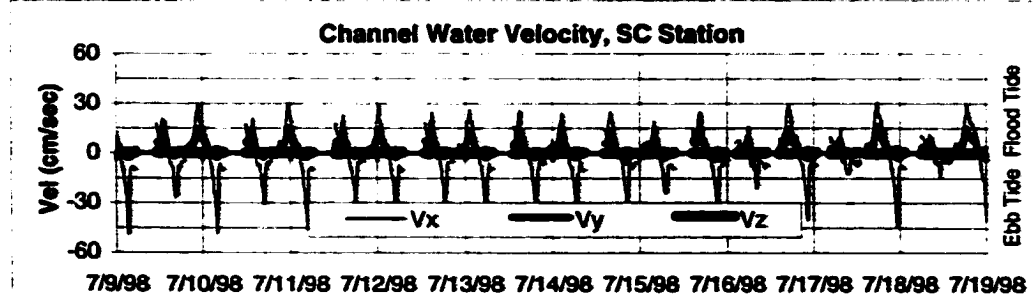
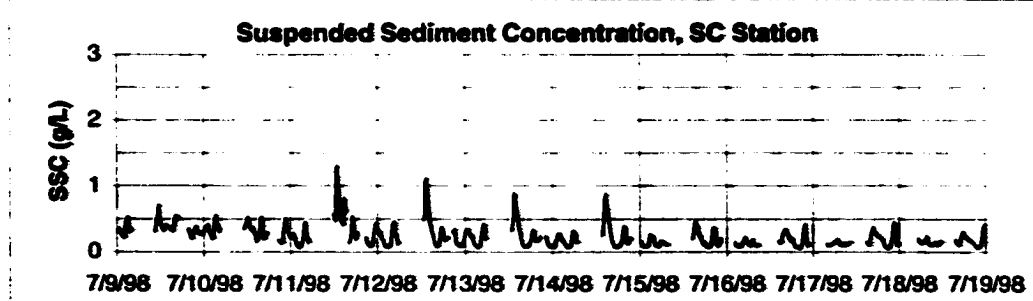
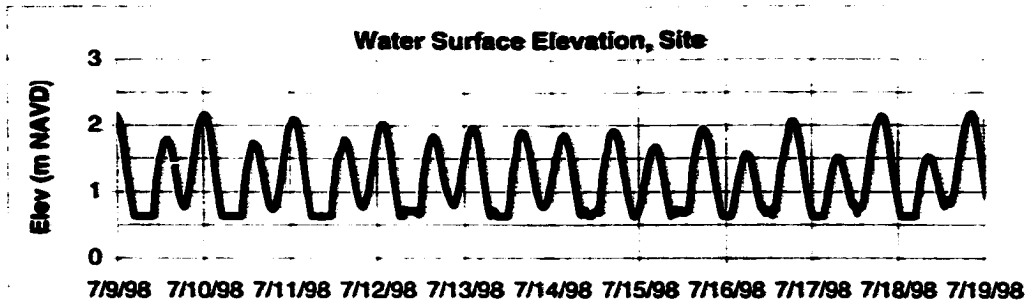
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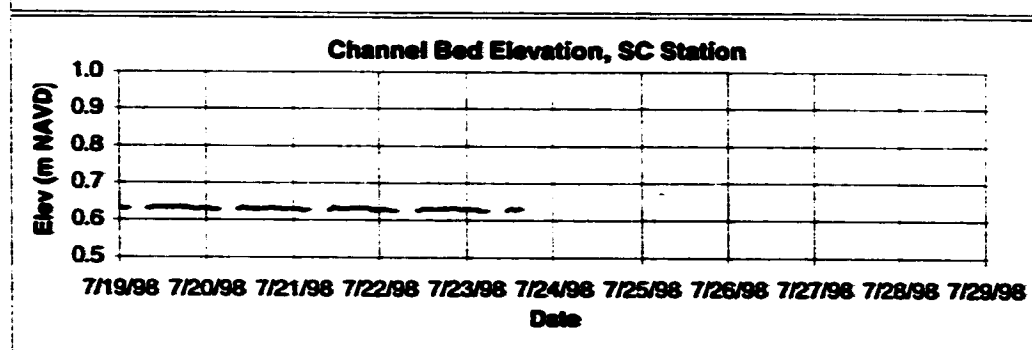
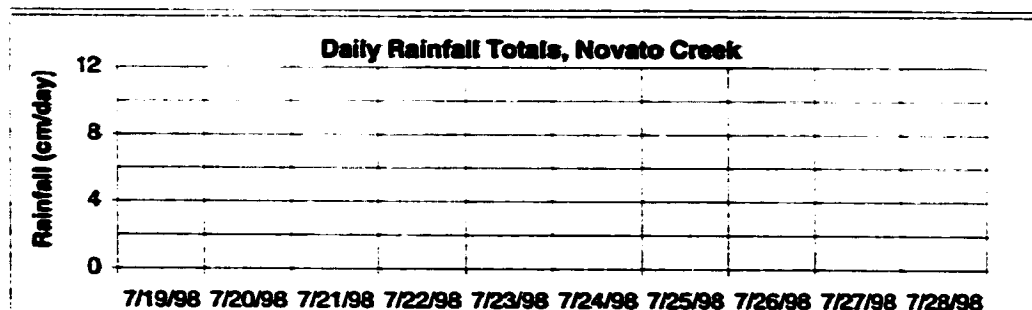
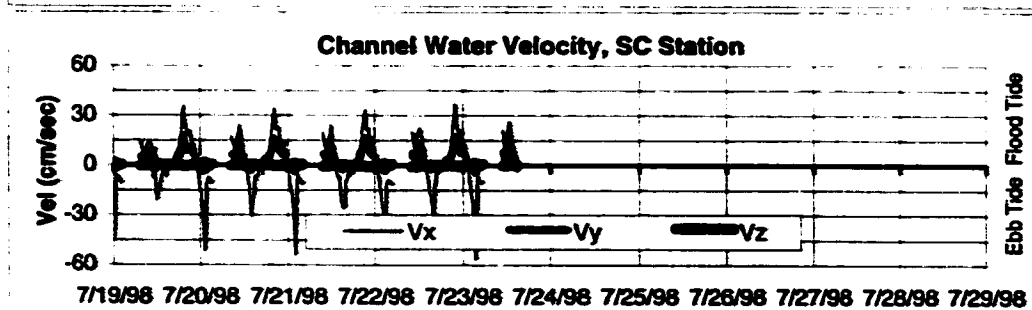
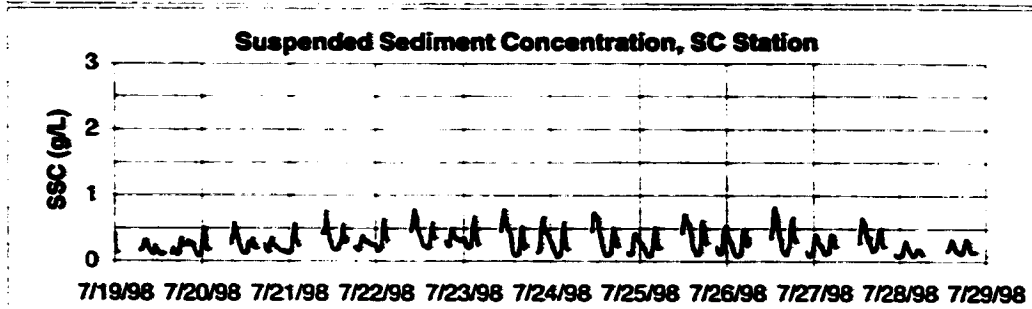
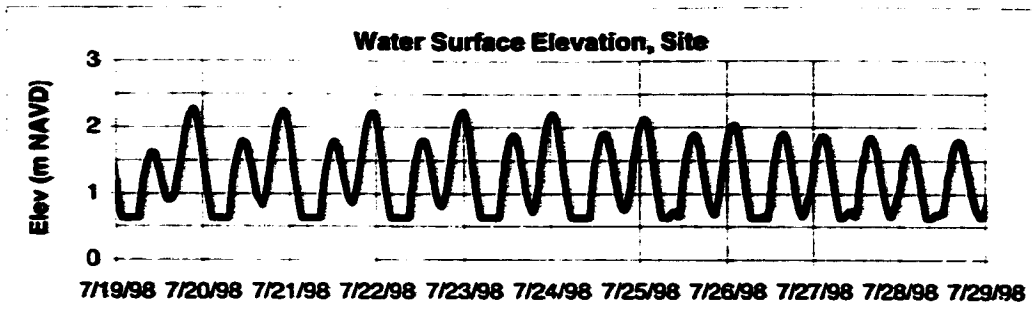


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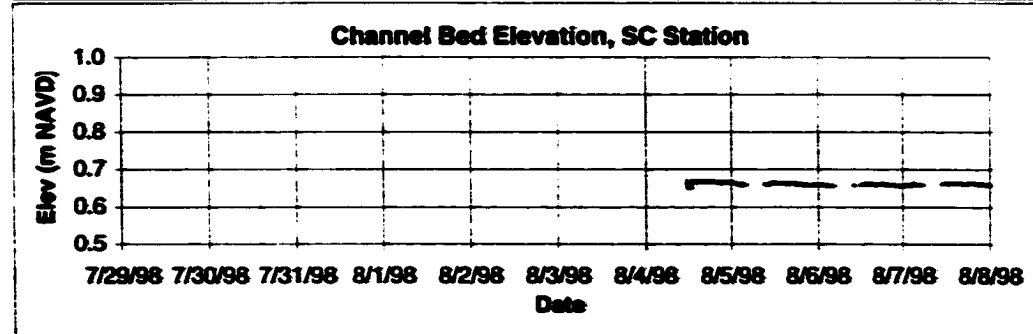
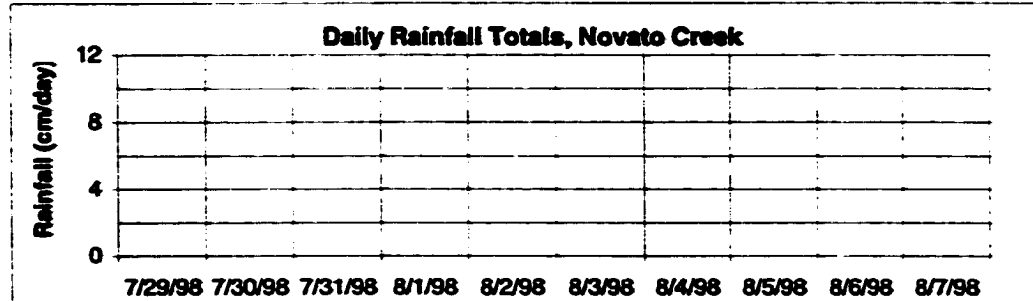
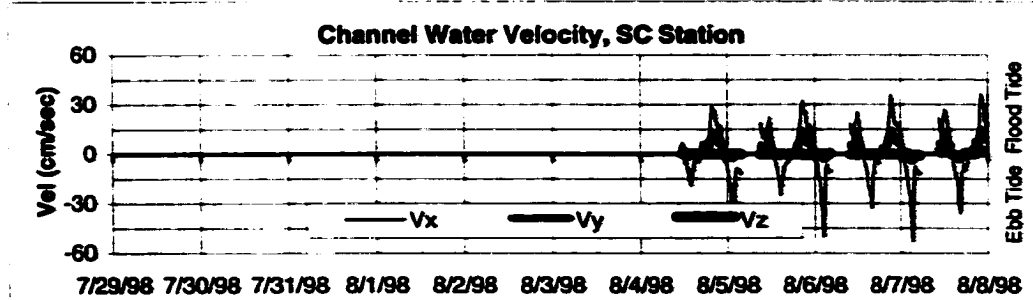
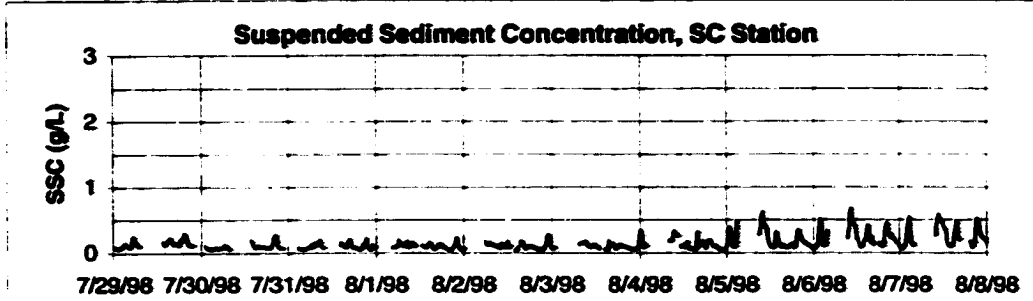
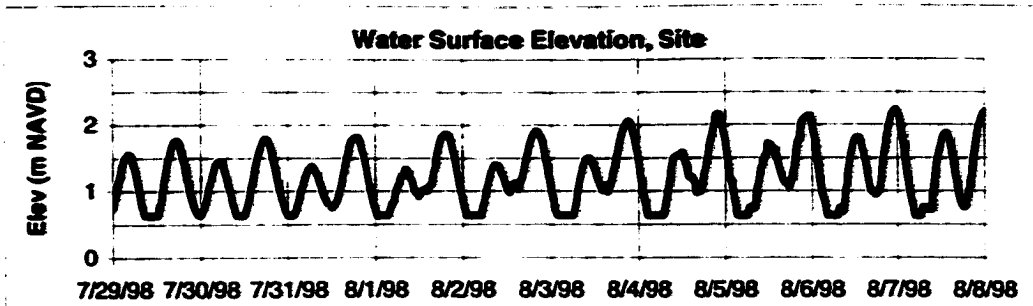


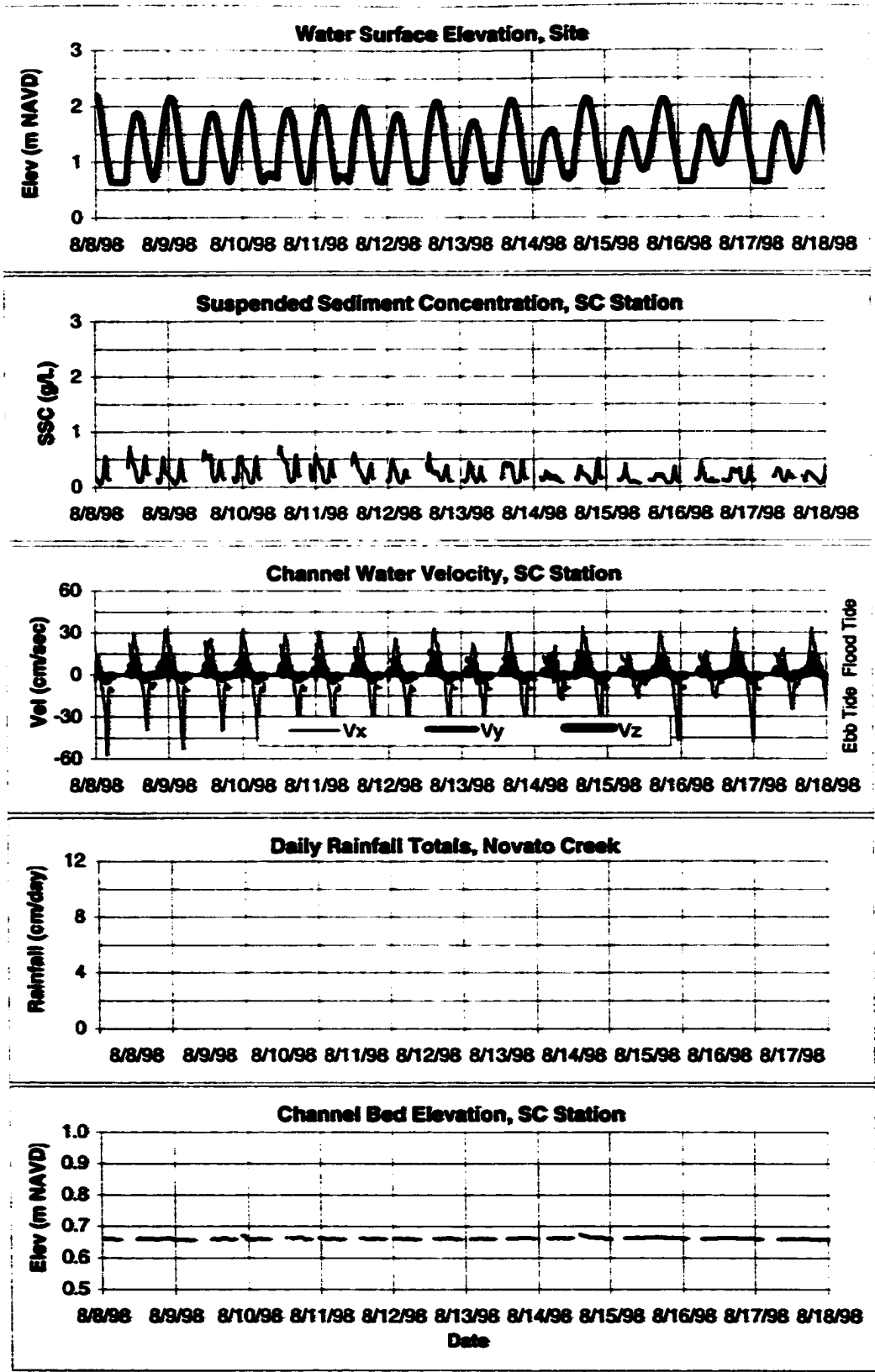
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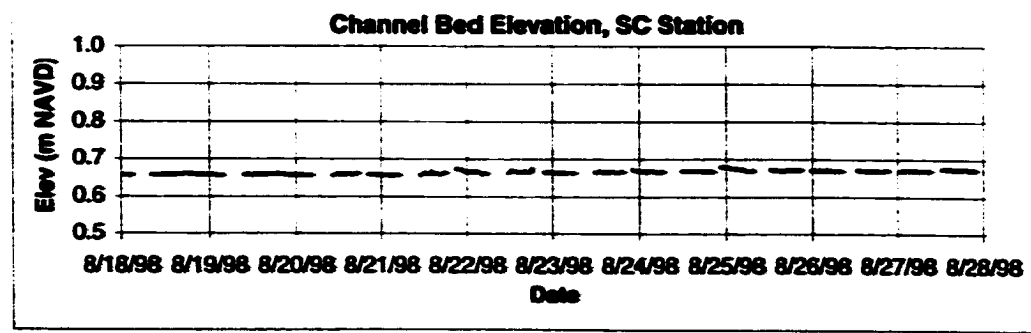
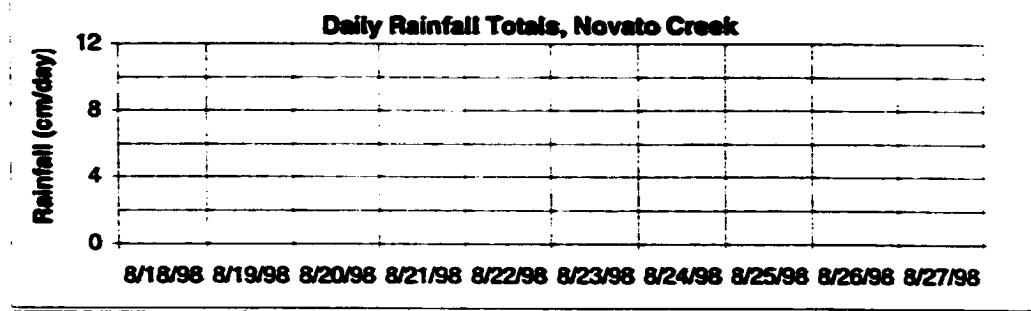
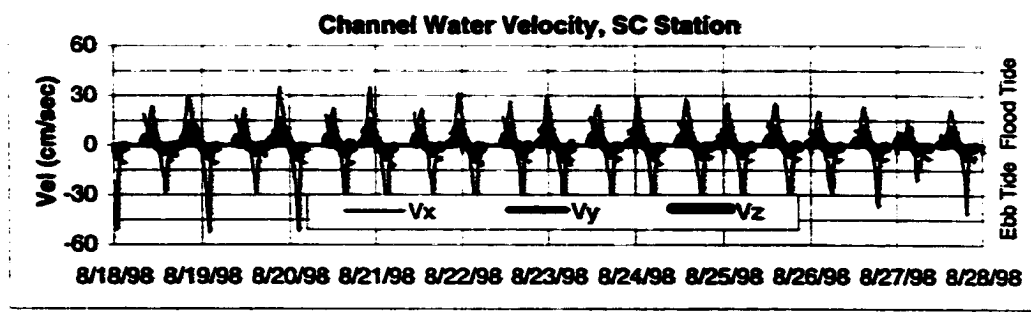
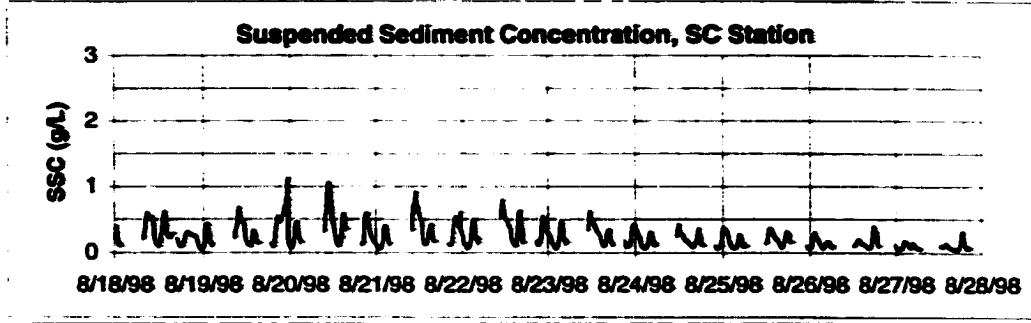
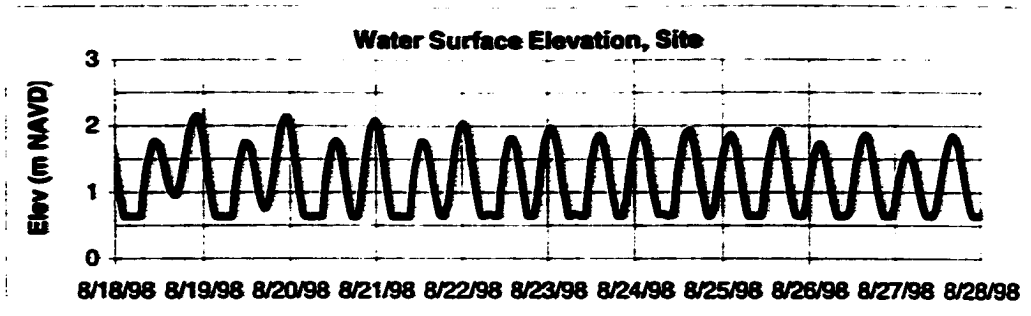


App B (5-23-02).xls: 19

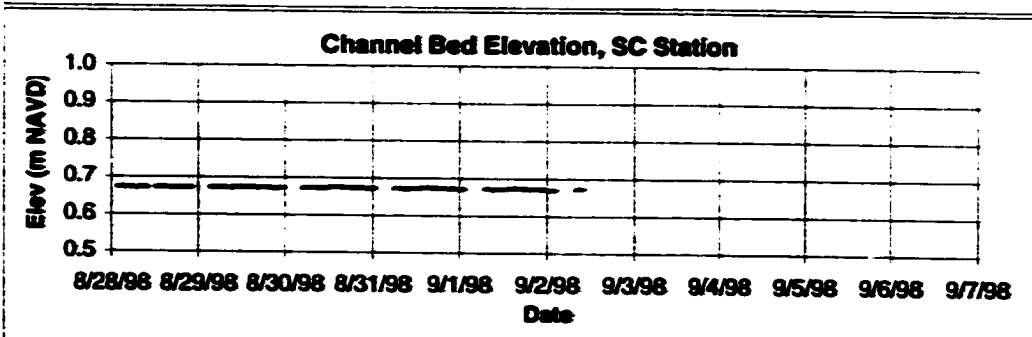
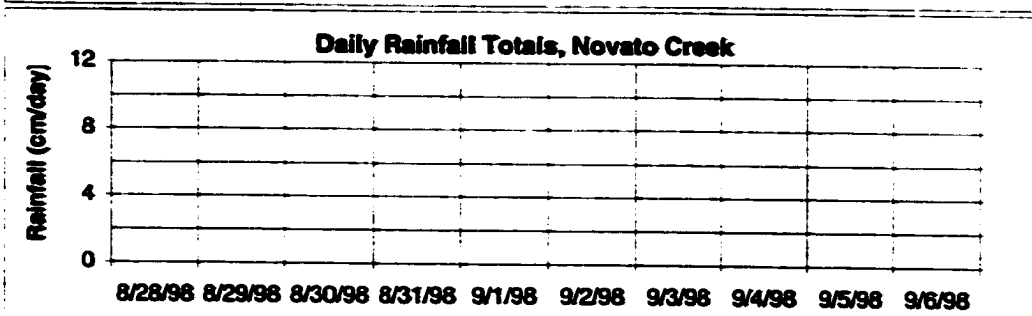
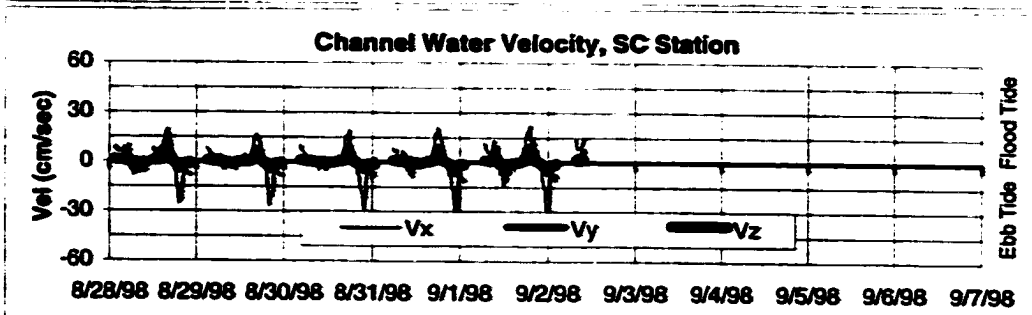
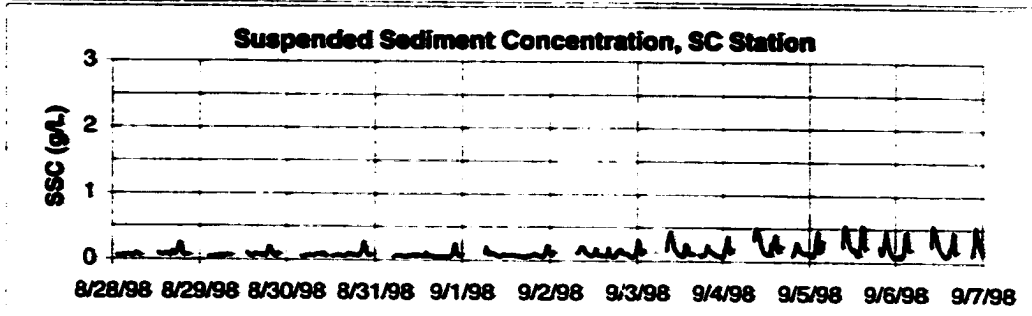
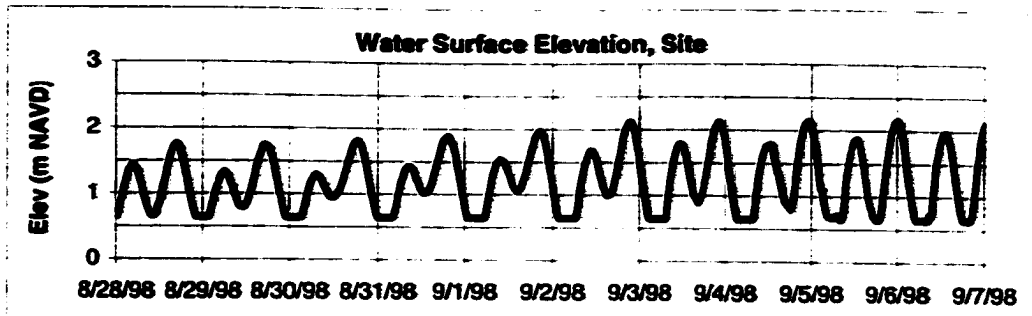




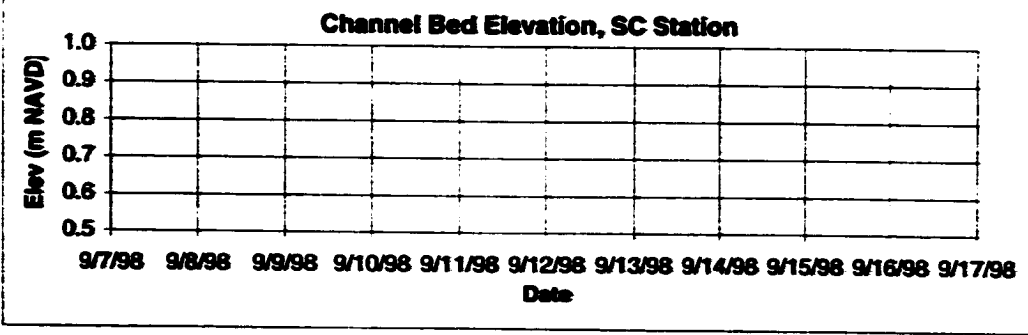
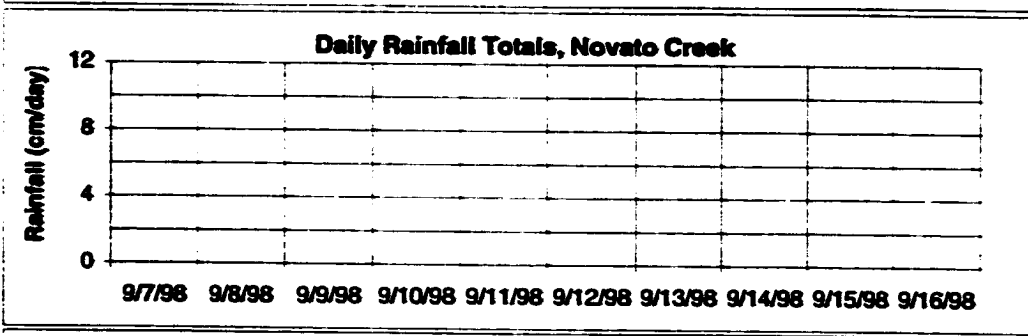
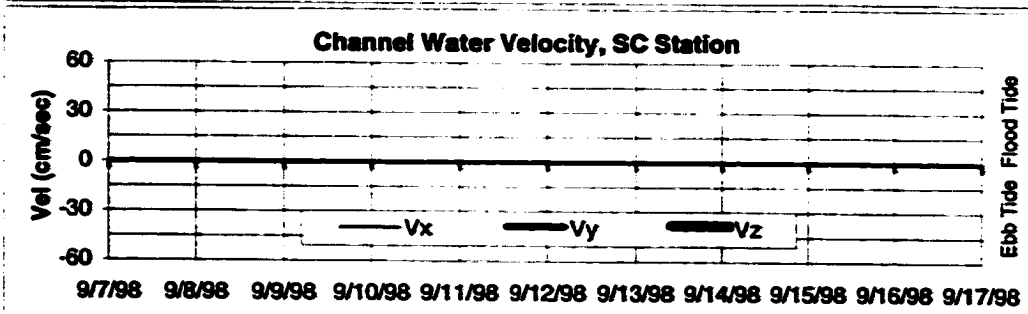
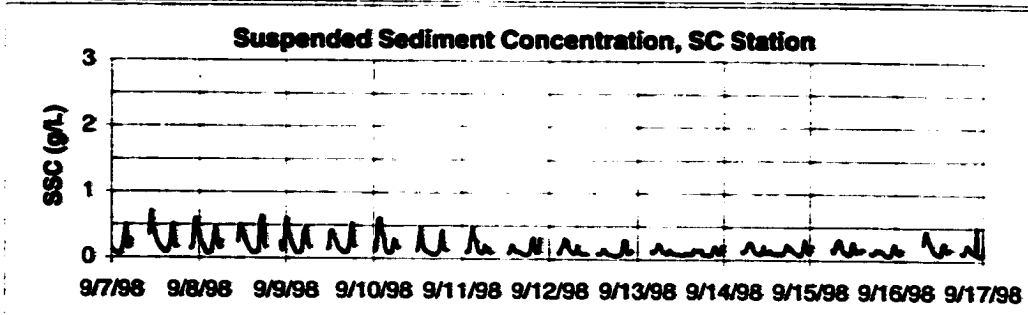
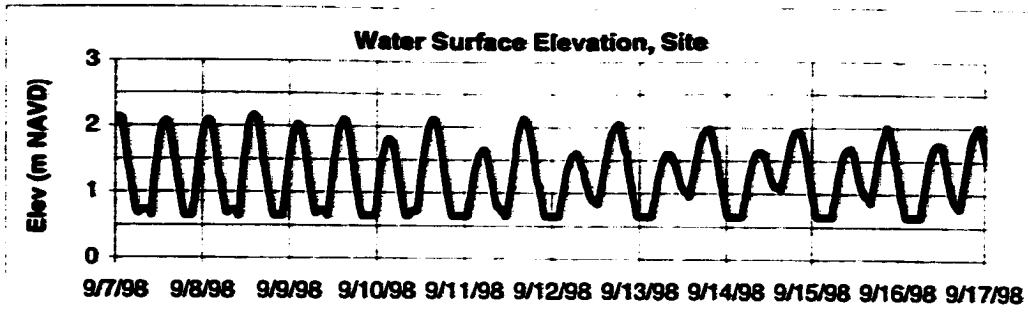
App B (5-23-02).xls: 21



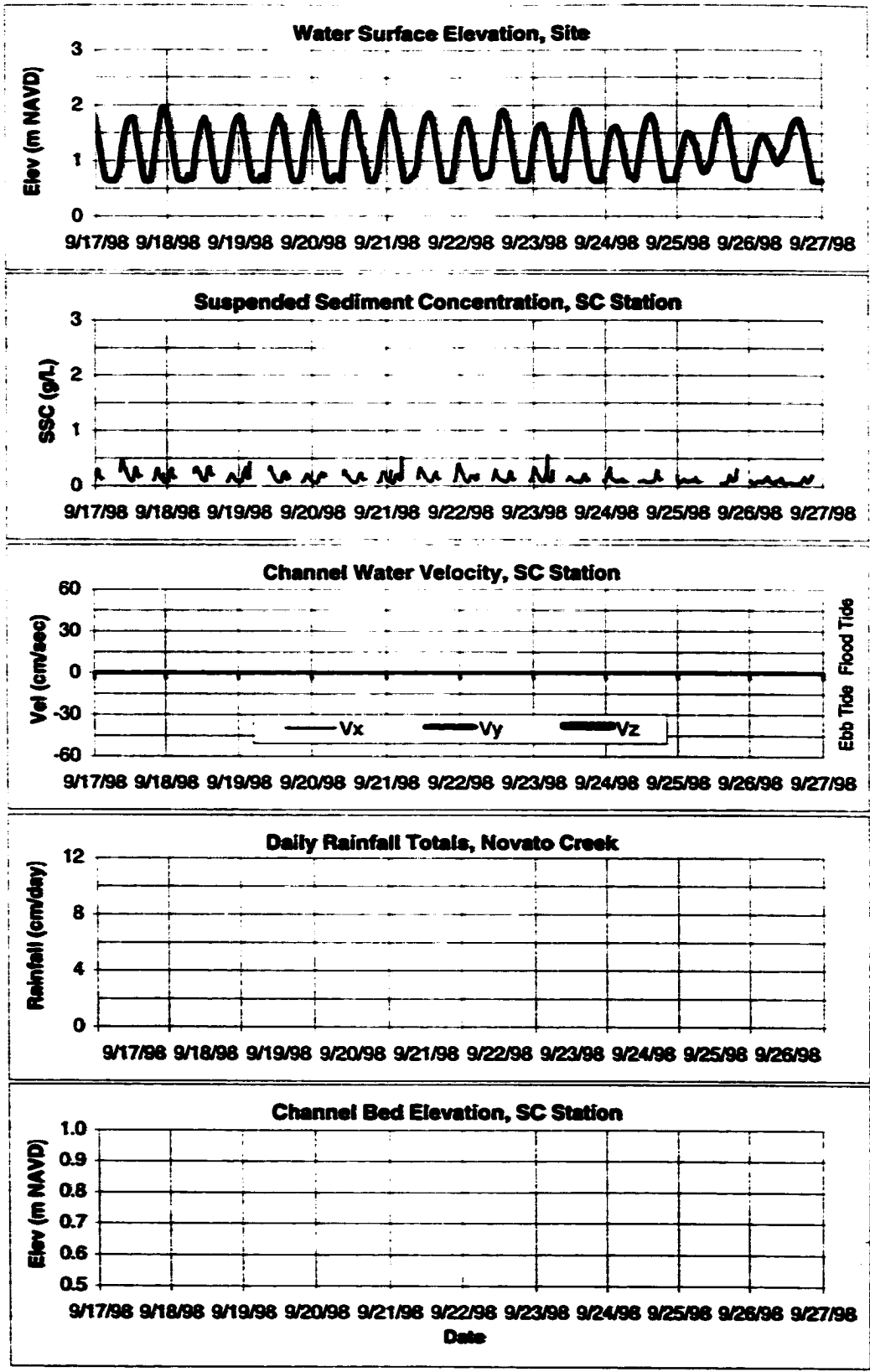
App B (5-23-02).xls 22



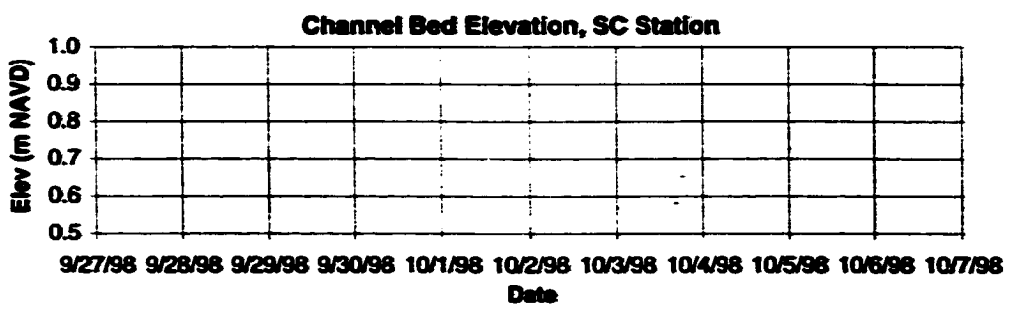
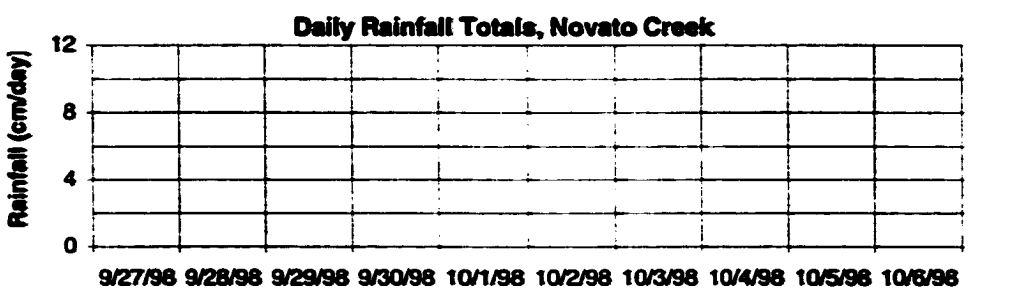
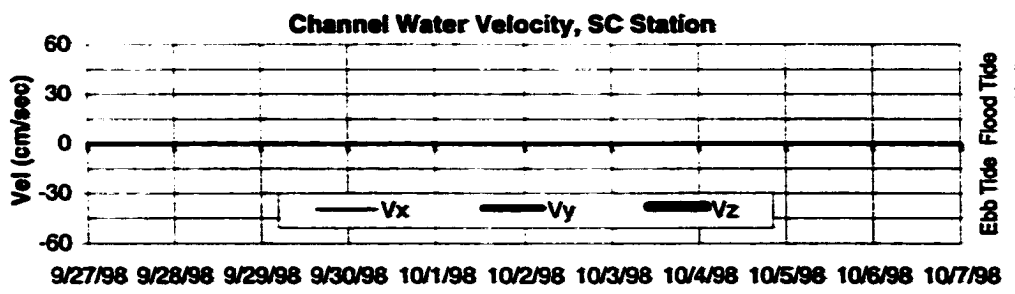
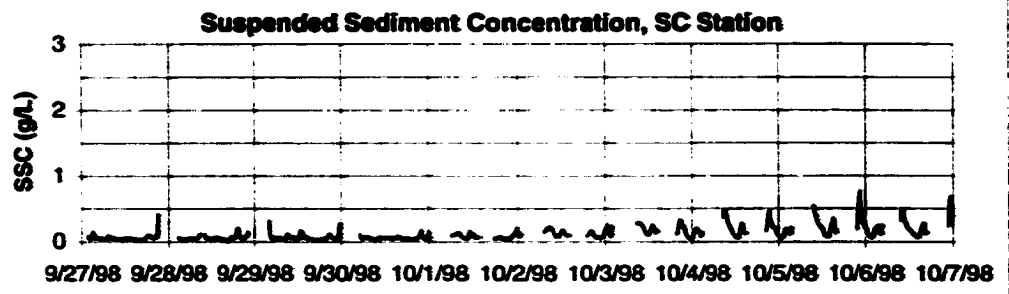
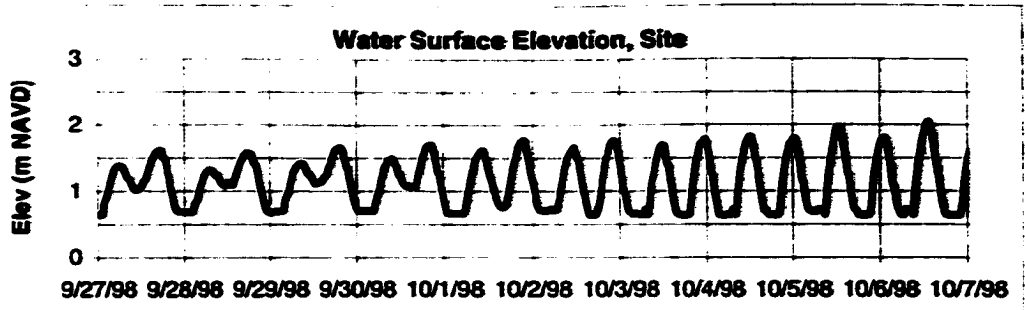
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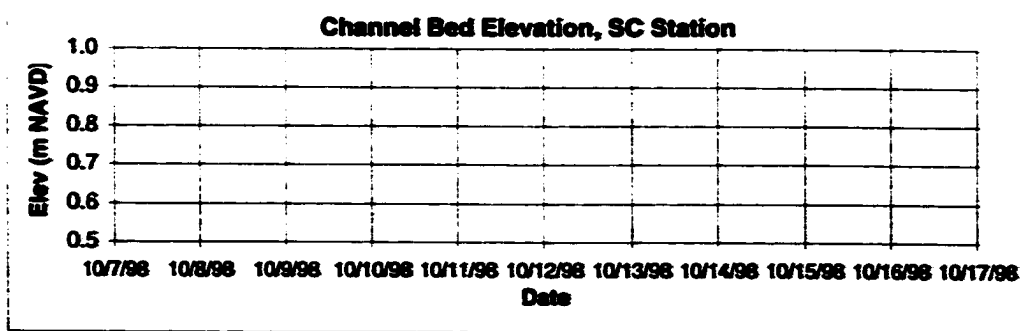
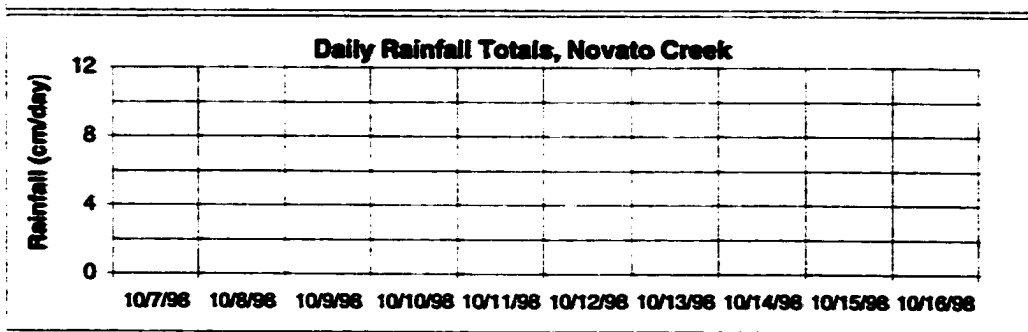
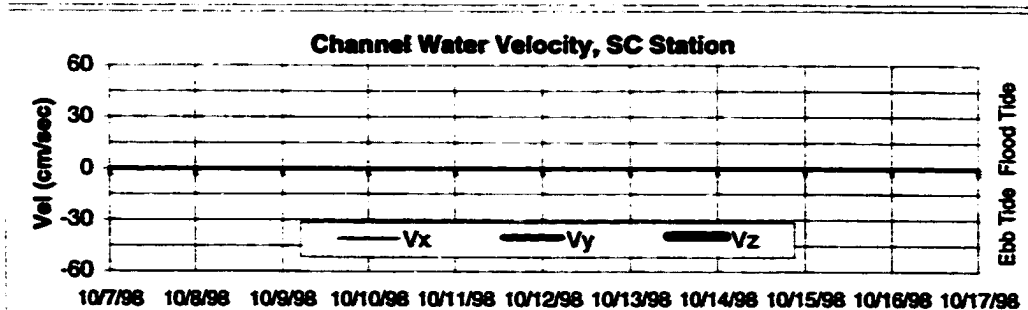
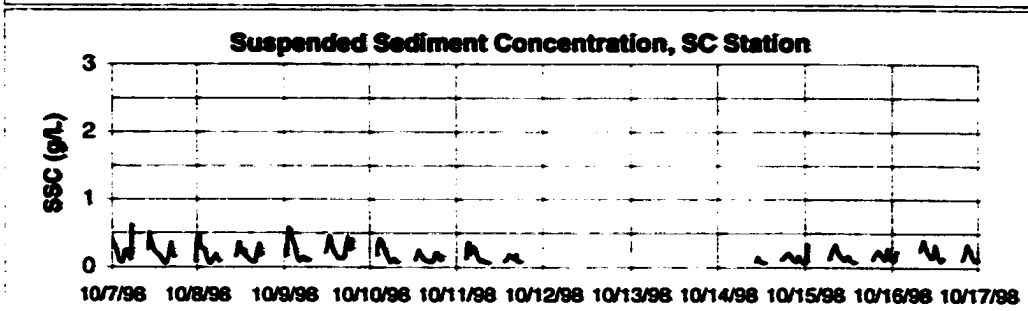
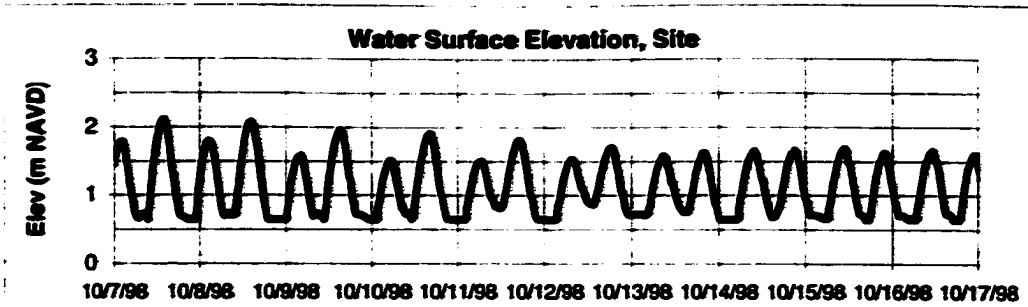
App B (5-23-02).xls: 24



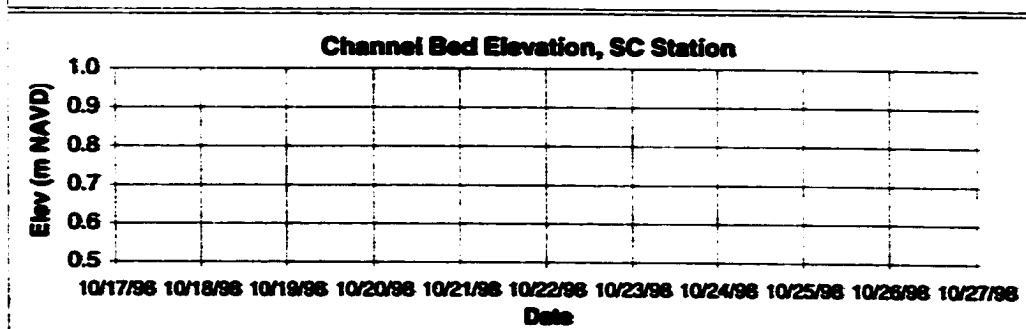
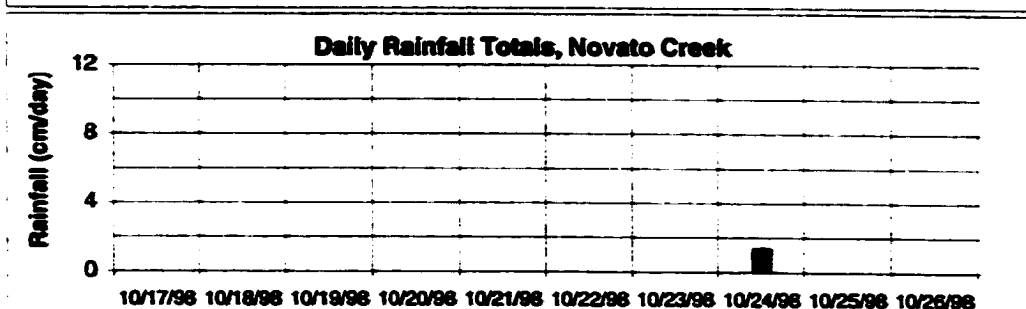
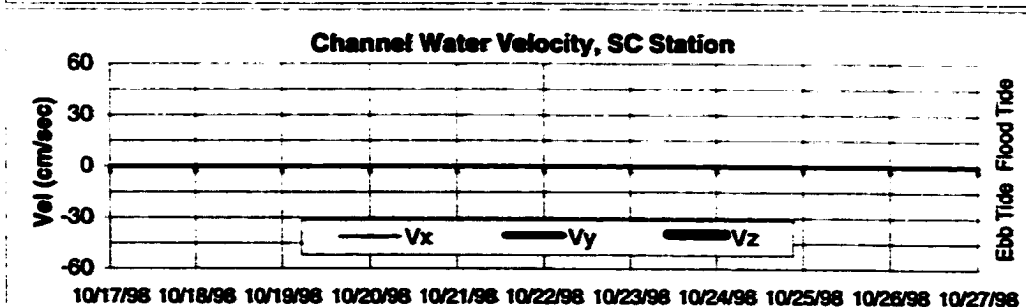
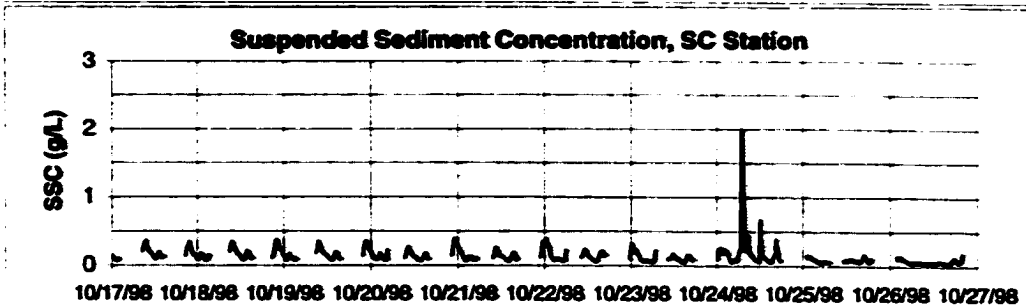
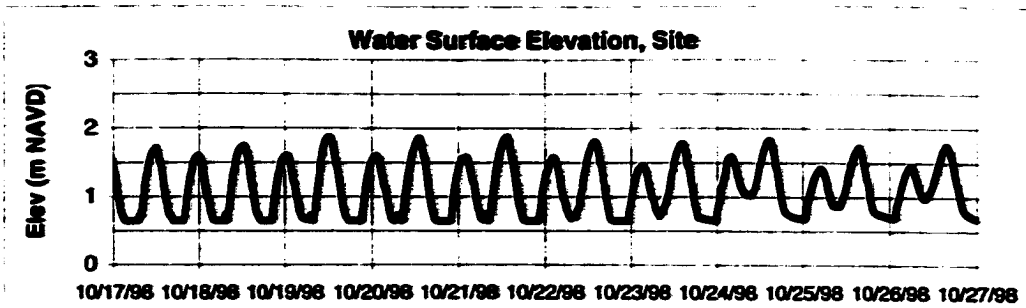
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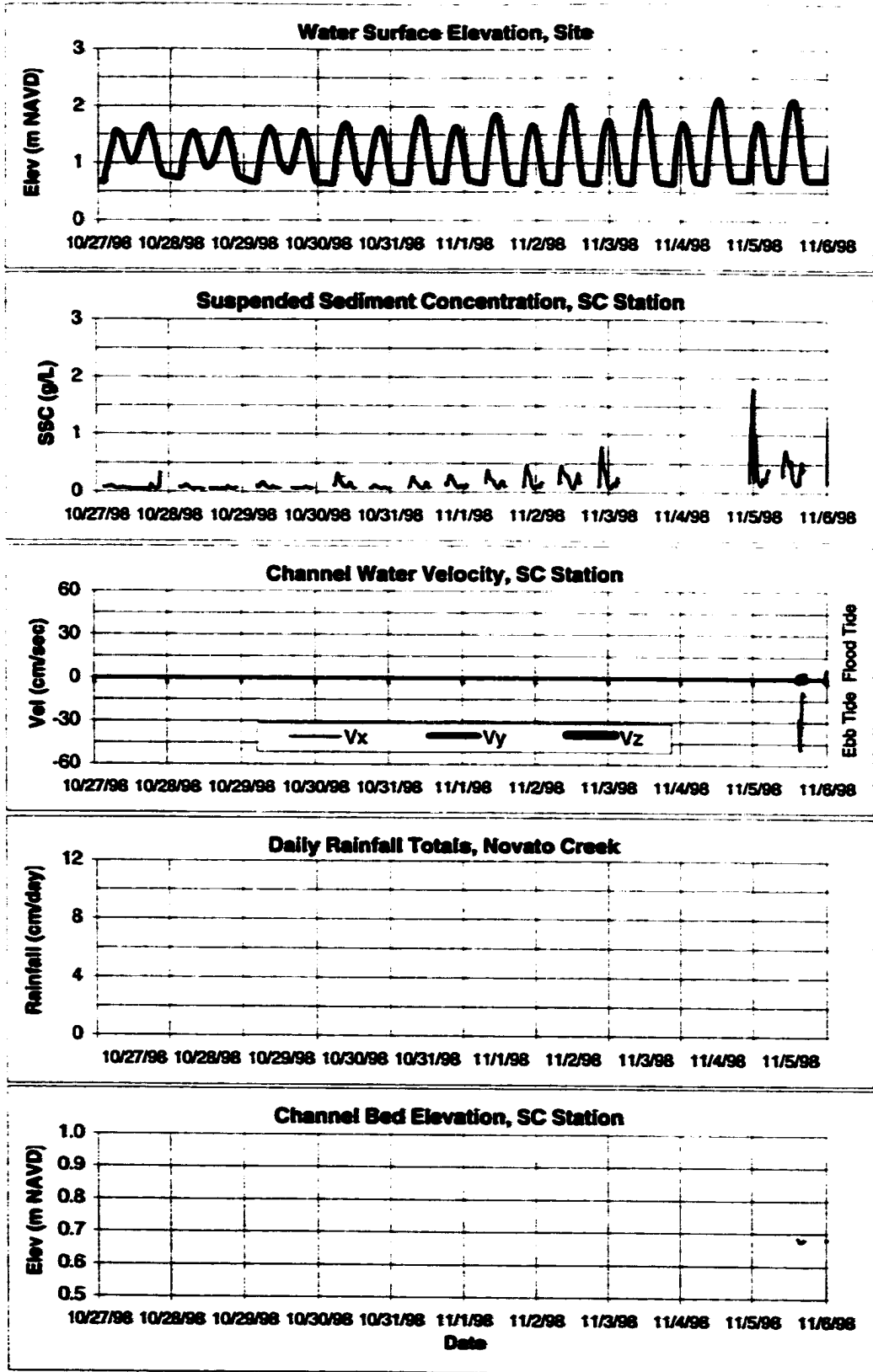


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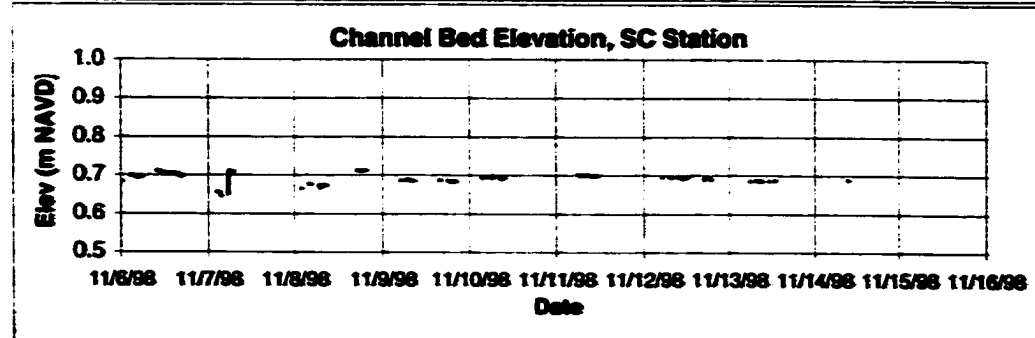
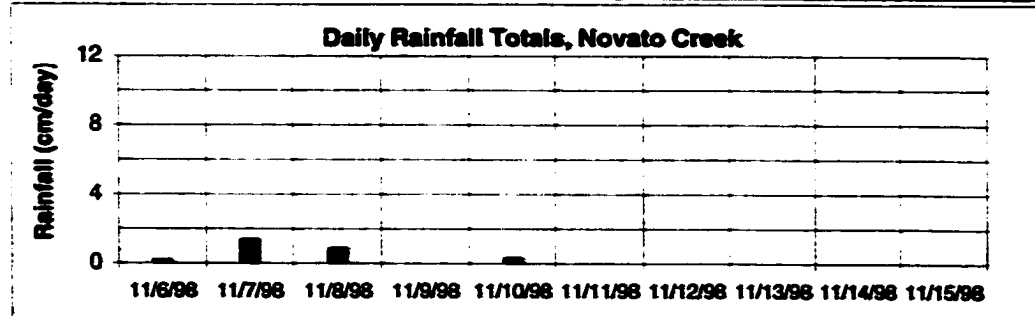
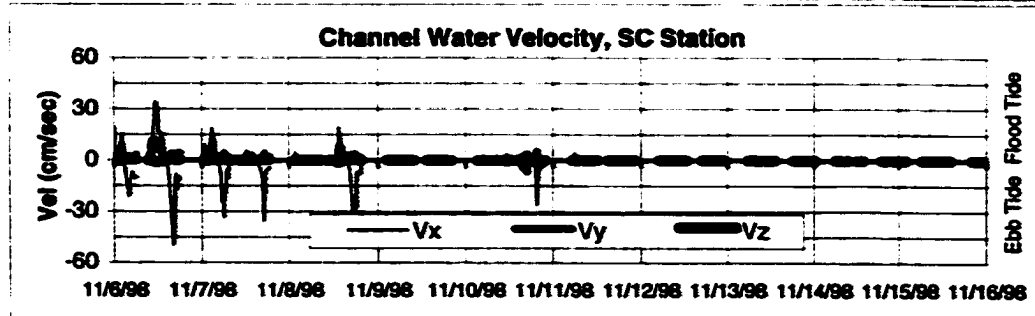
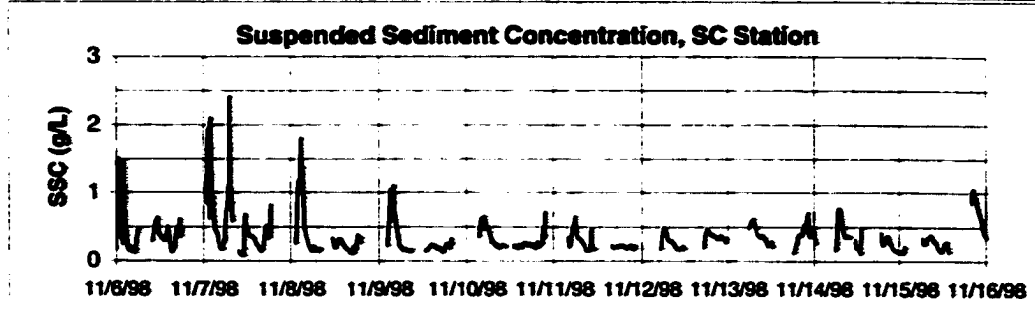
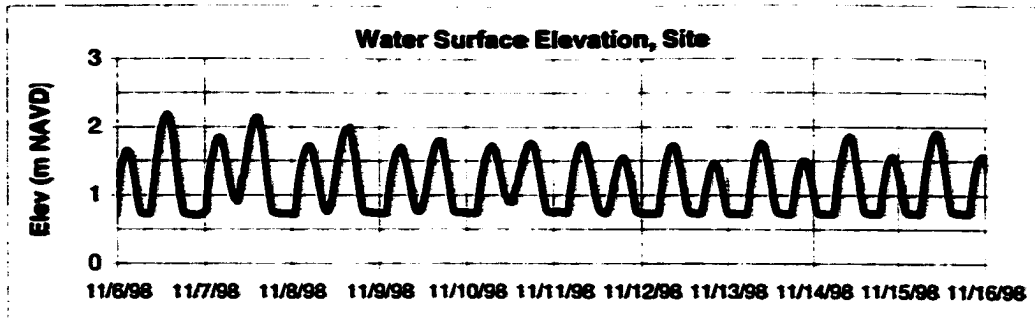


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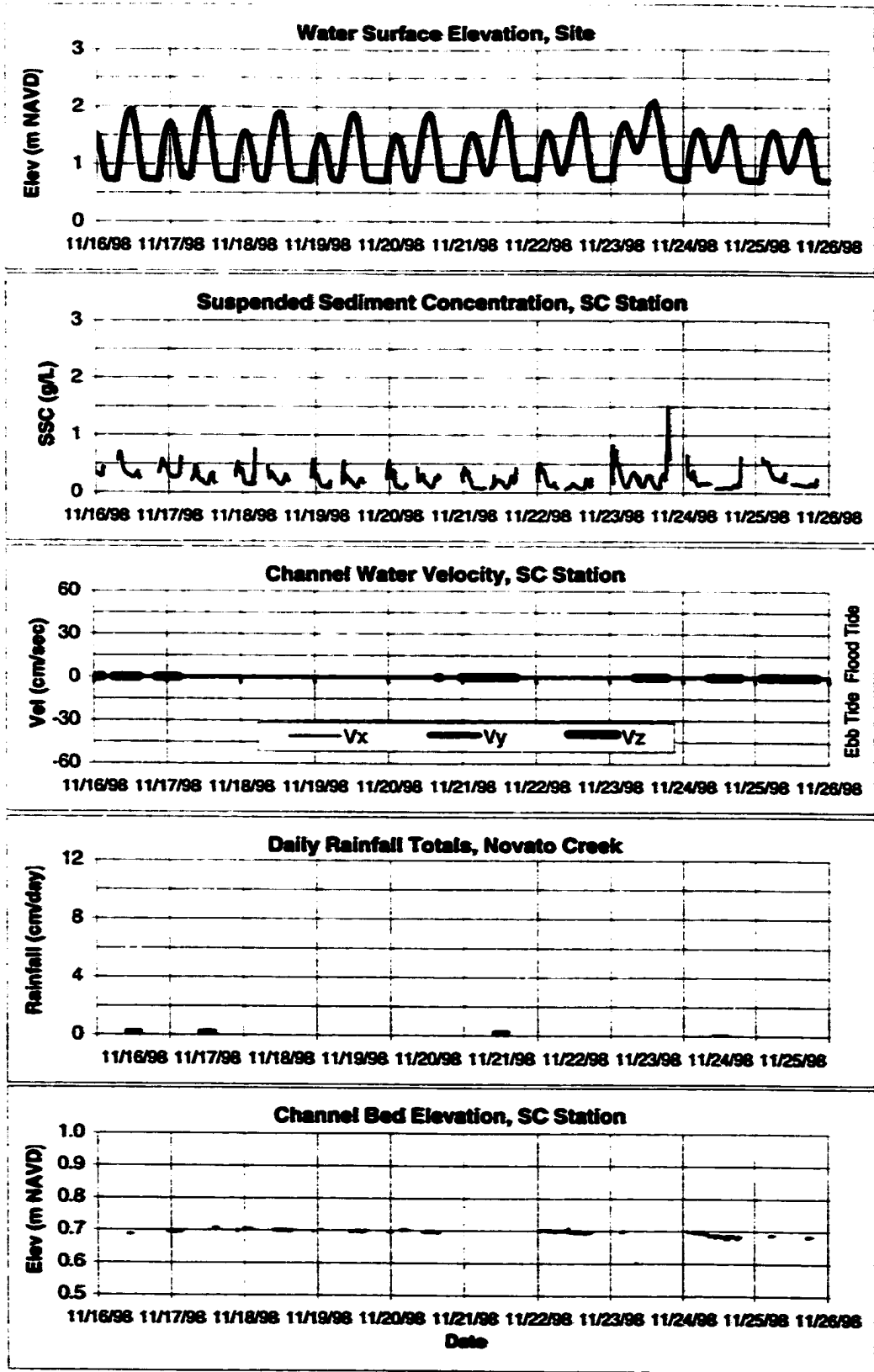




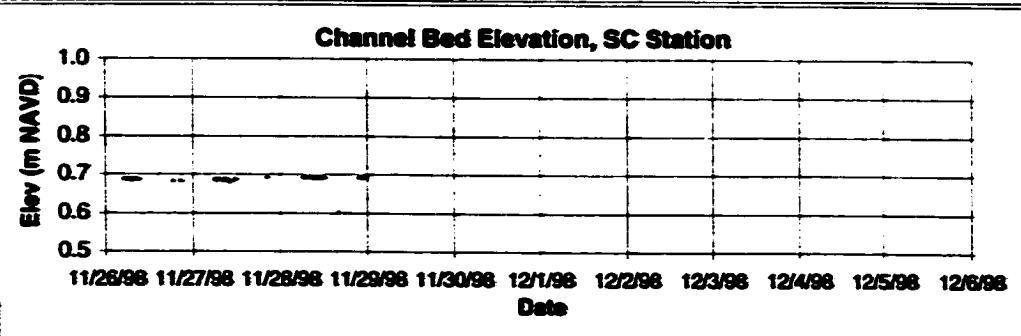
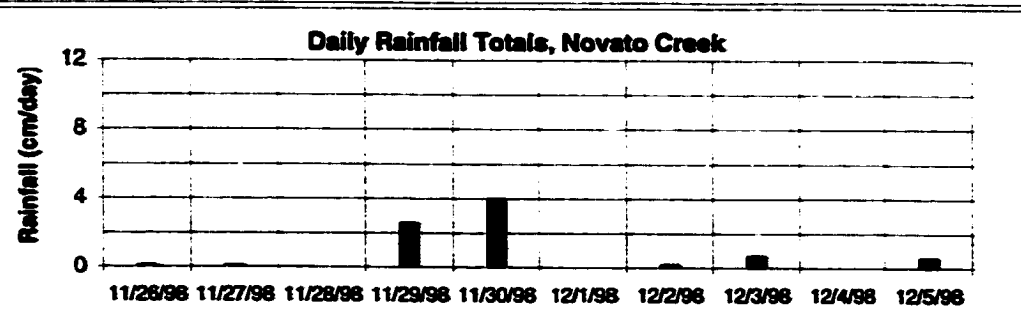
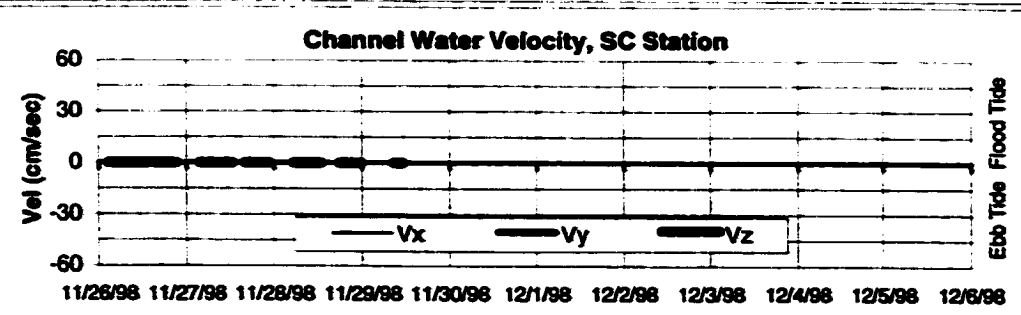
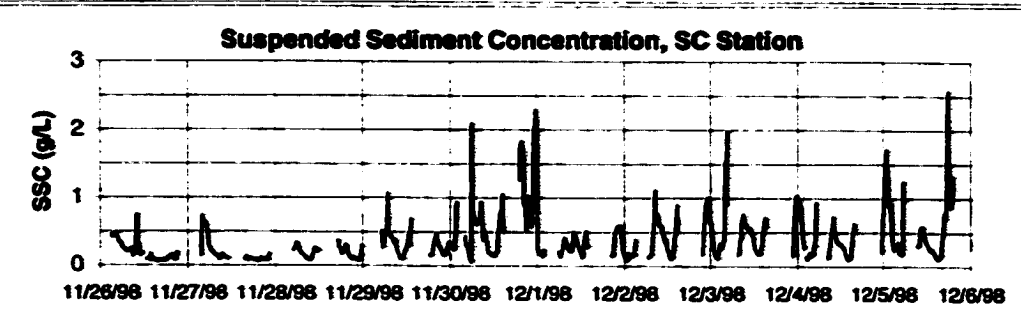
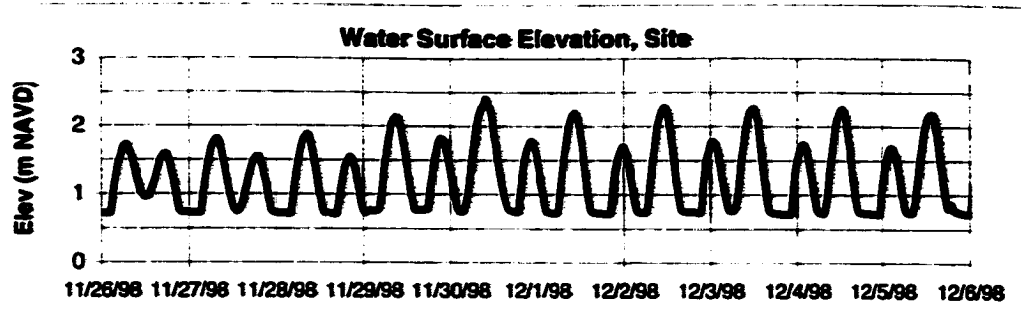
App 5 (5-23-02).xls: 29



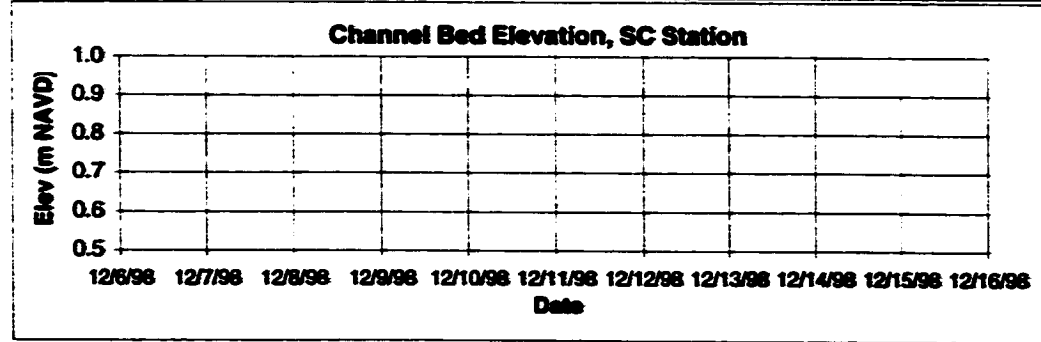
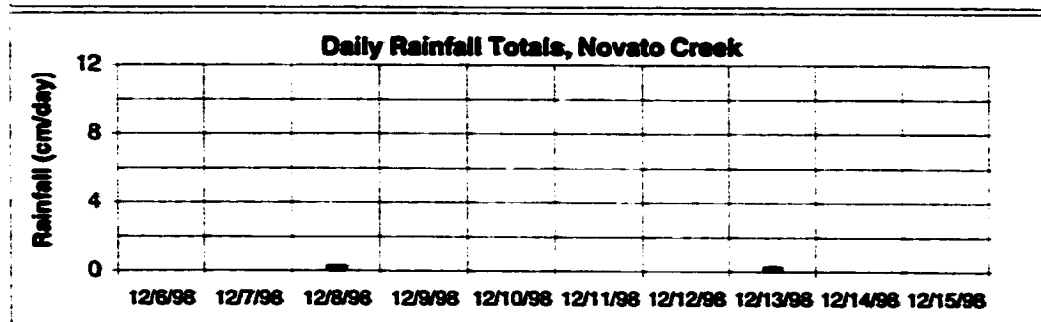
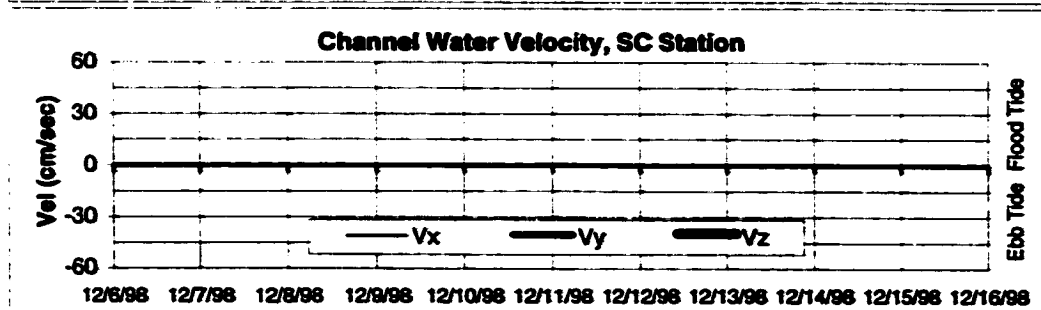
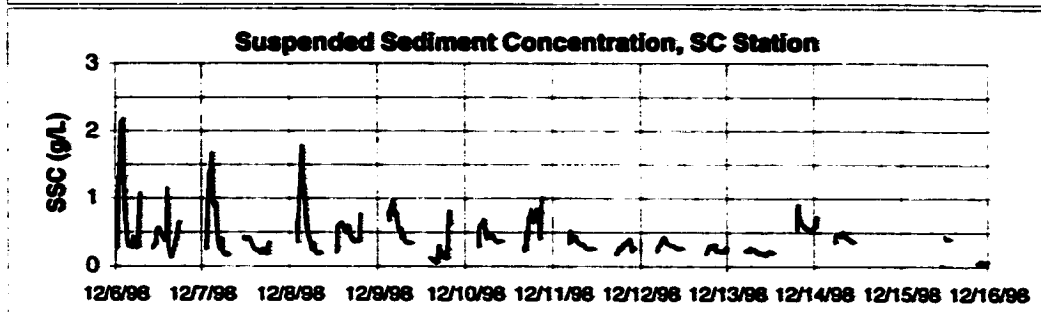
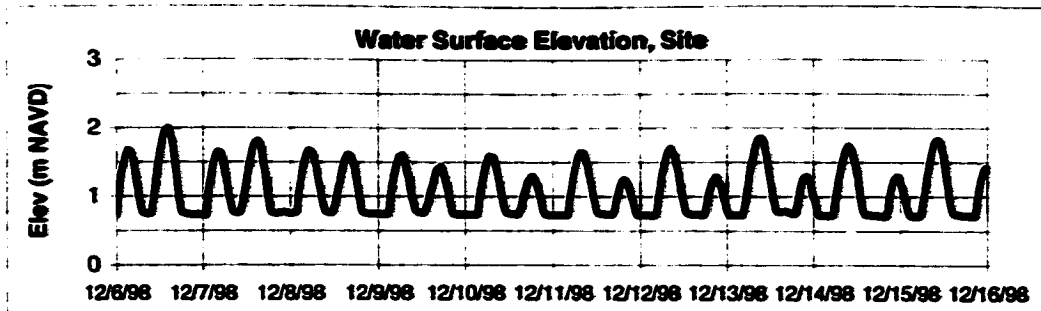
App B (5-23-02).xls: 30



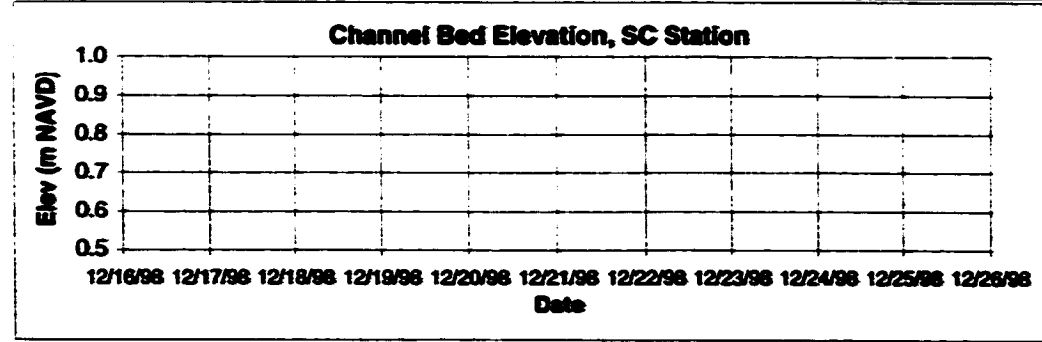
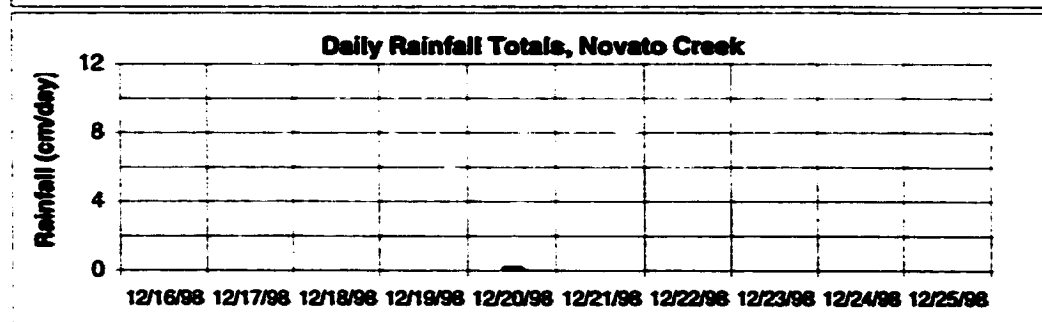
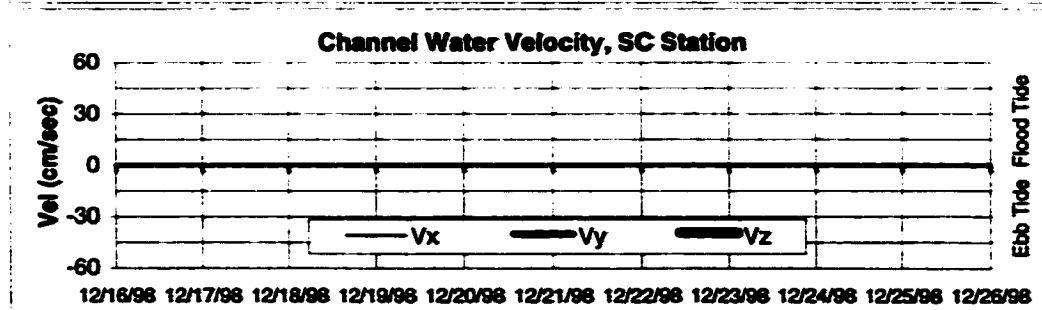
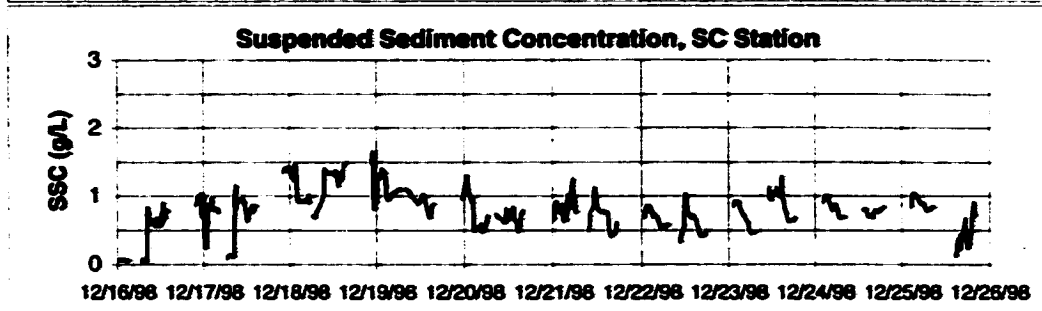
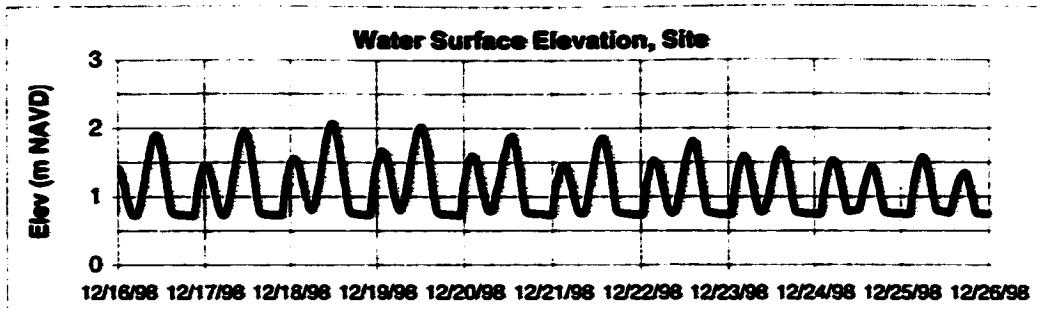
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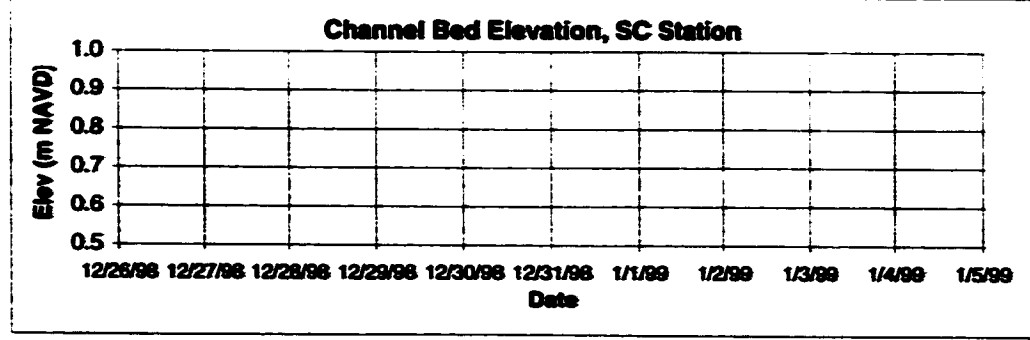
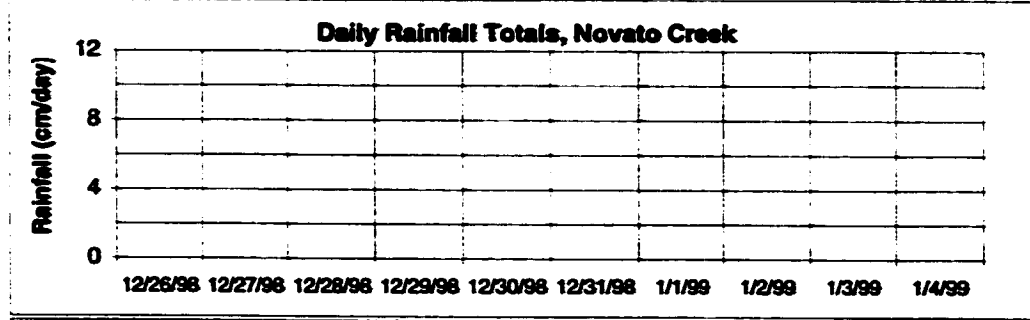
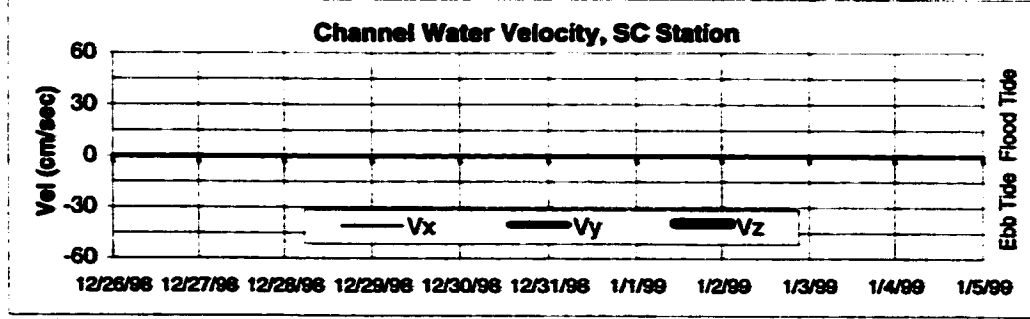
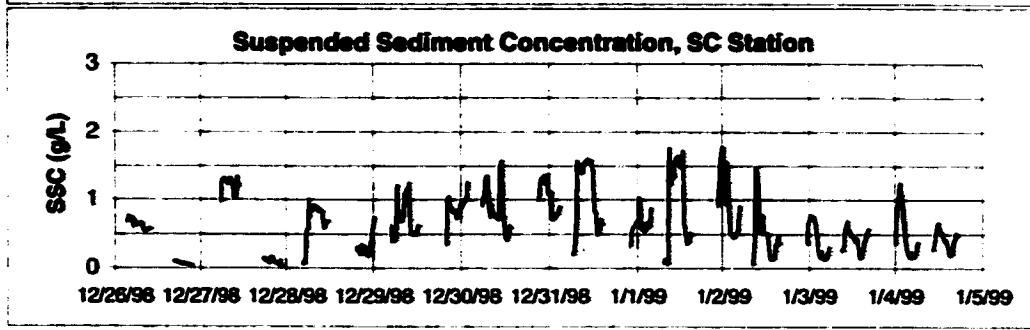
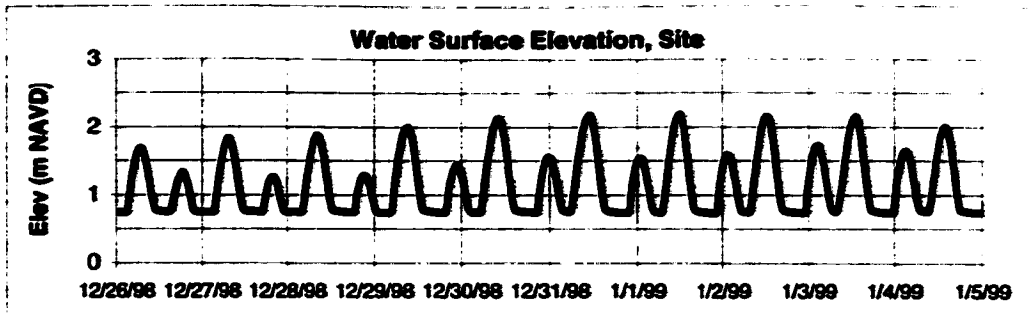
App B (5-23-02).xls: 32



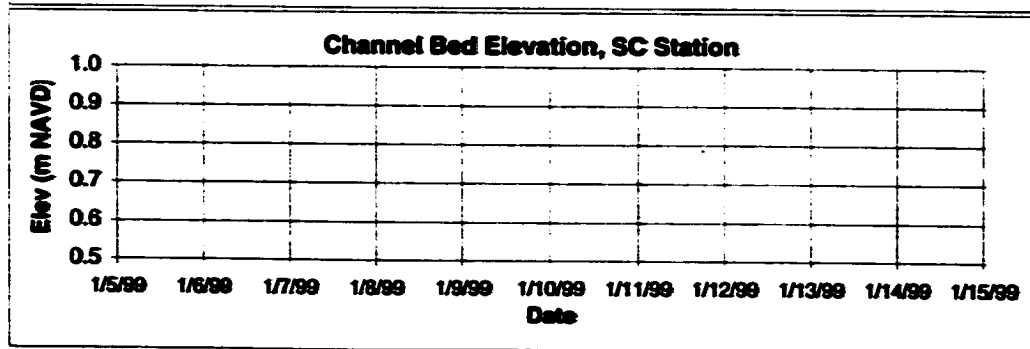
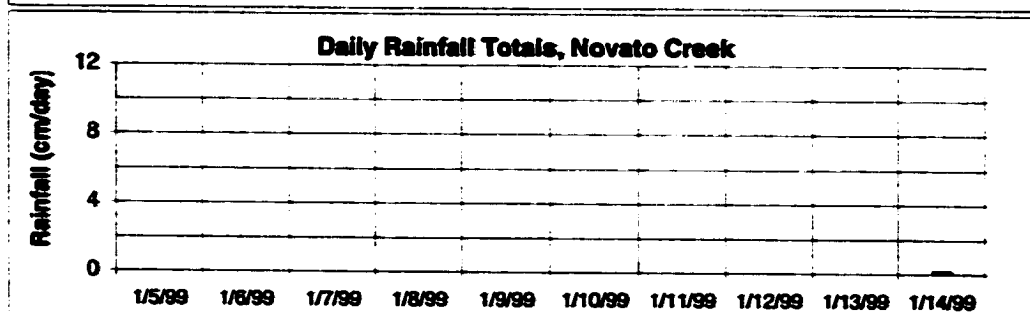
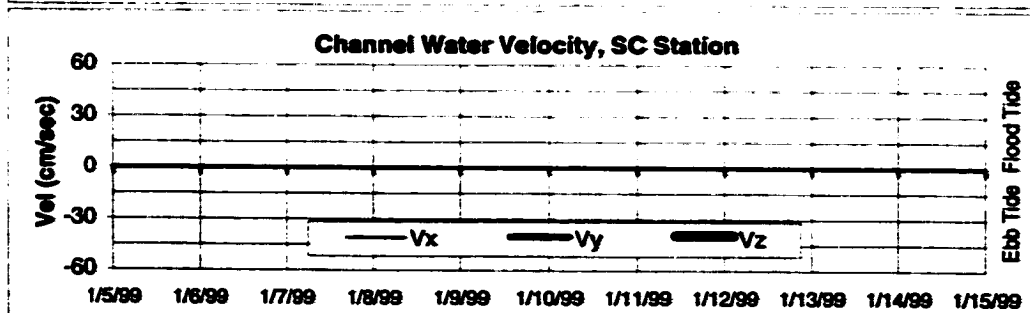
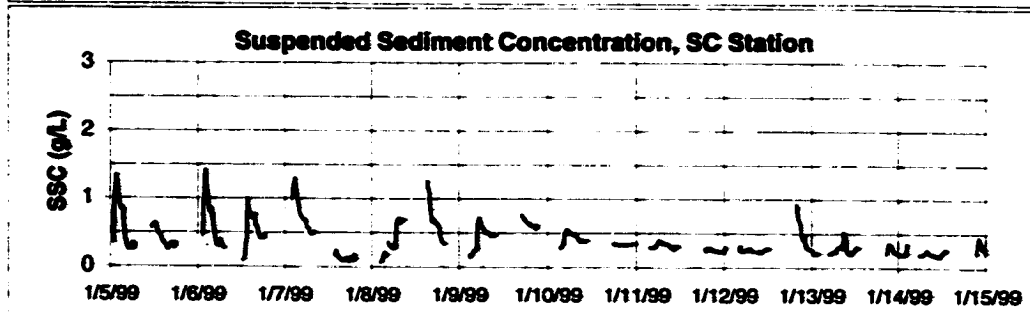
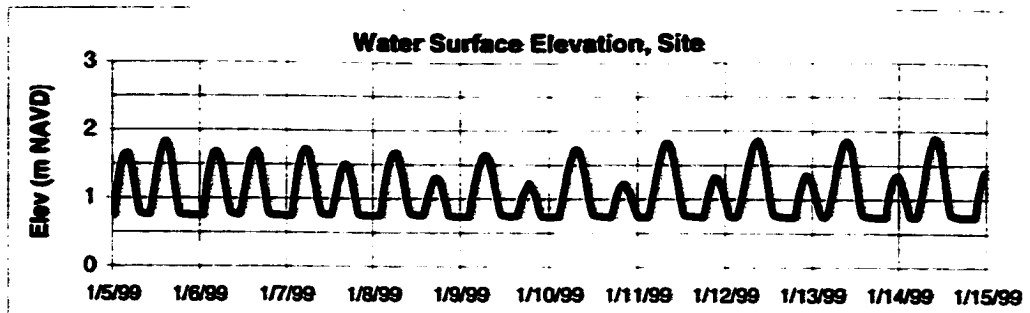
App B (5-23-02).xls: 33



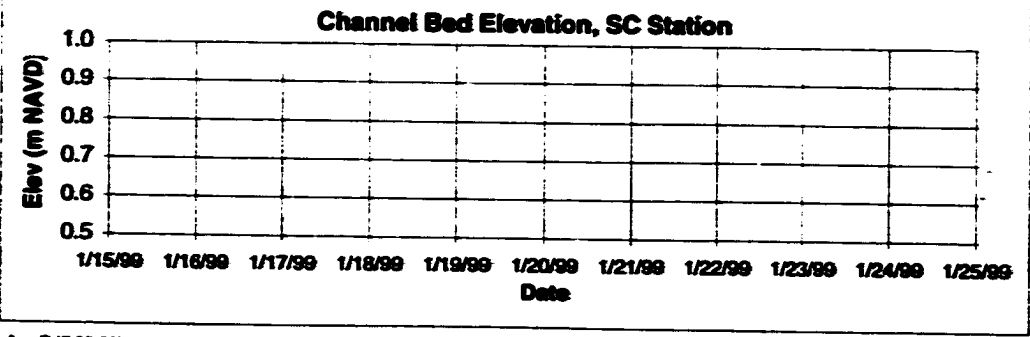
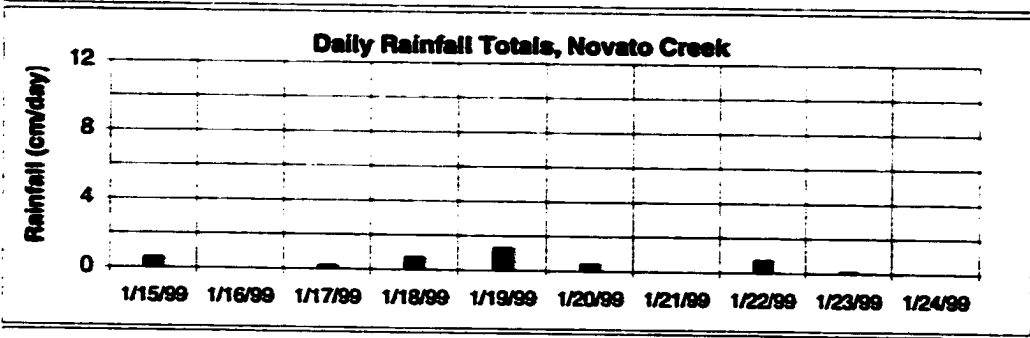
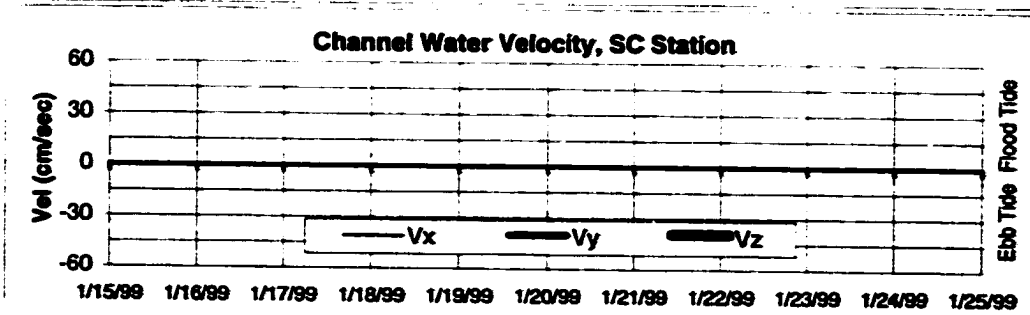
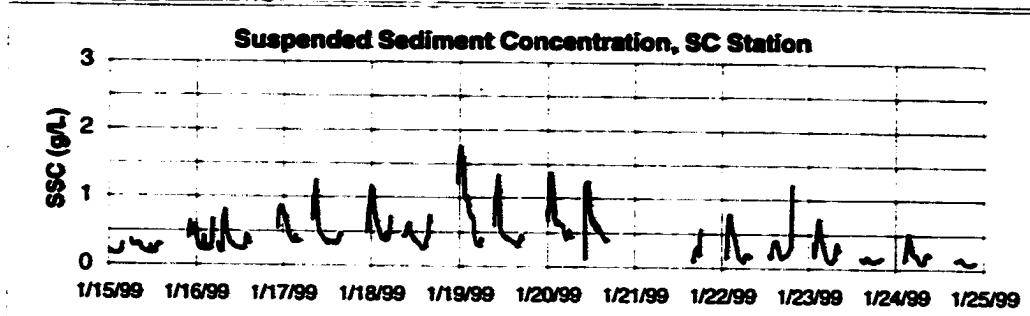
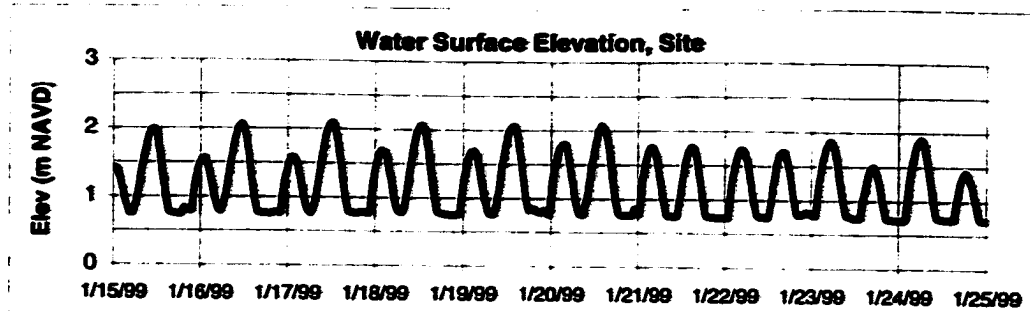
App B (5-23-02).xls: 34



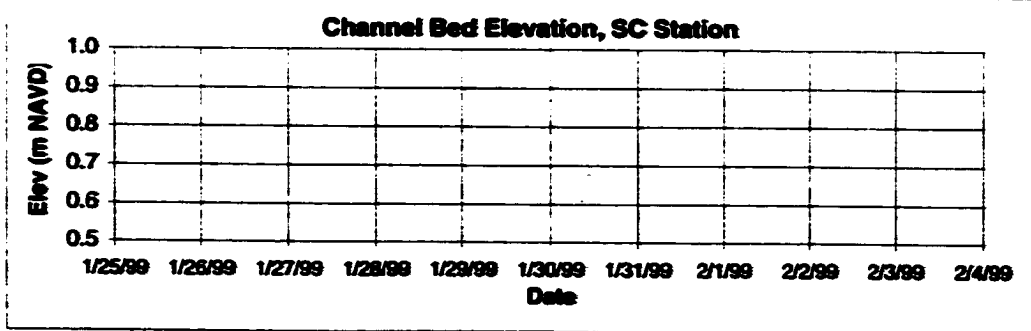
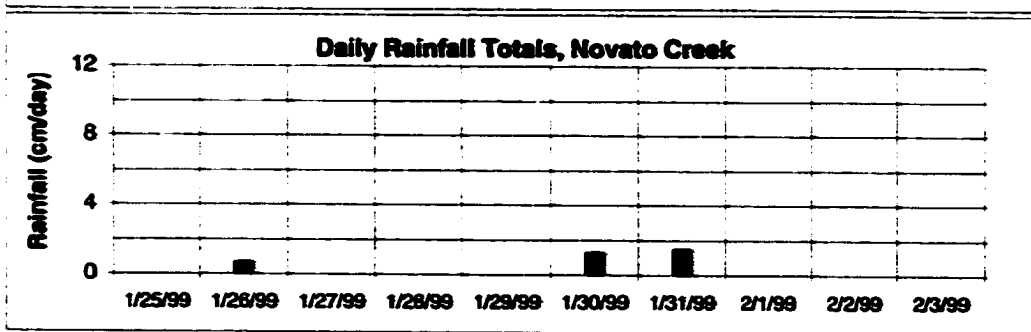
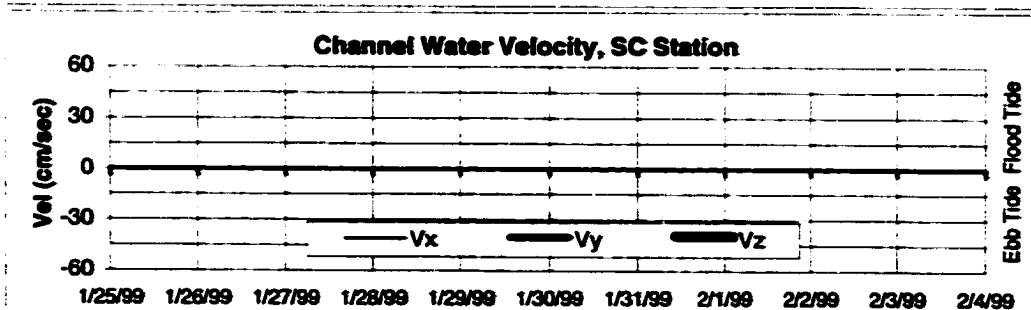
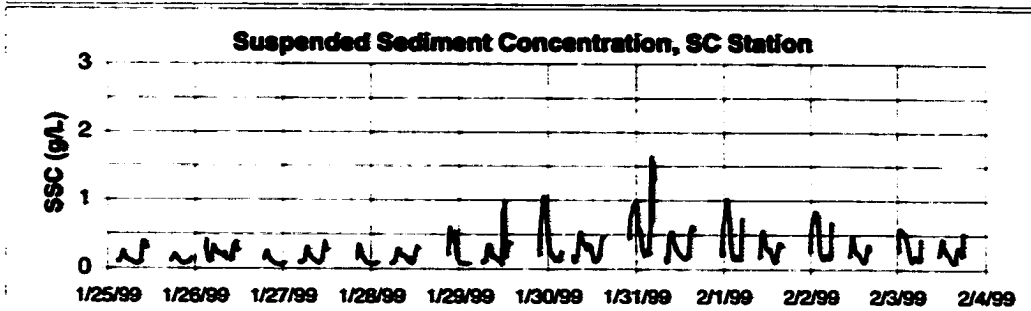
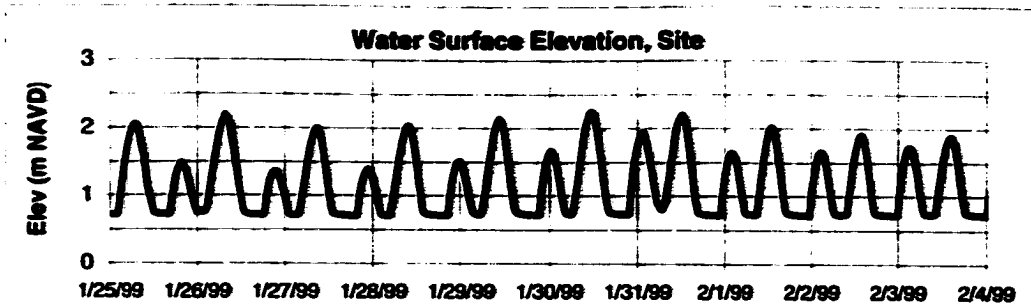
App B (5-23-02).xls 35



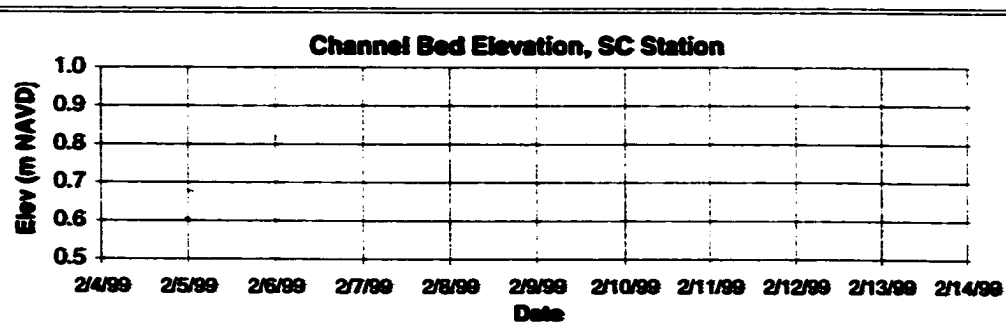
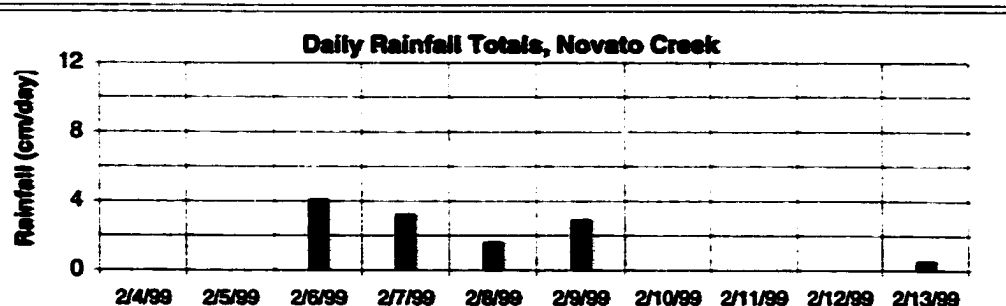
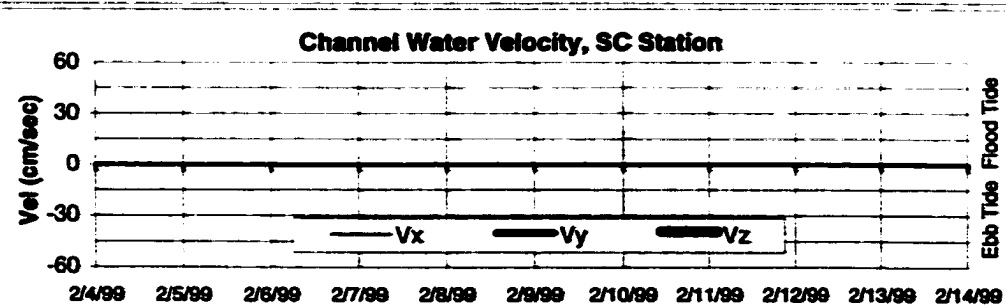
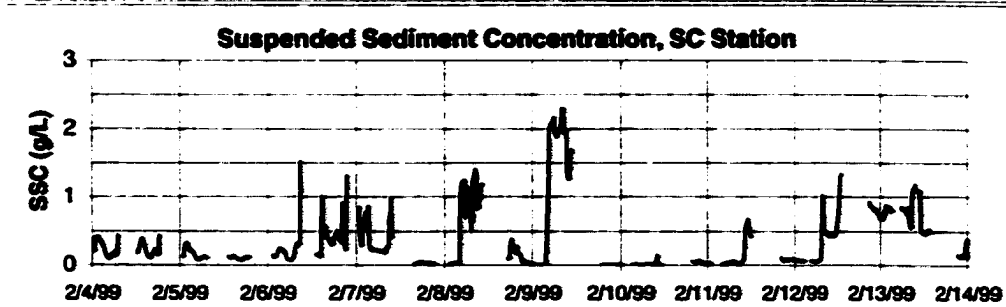
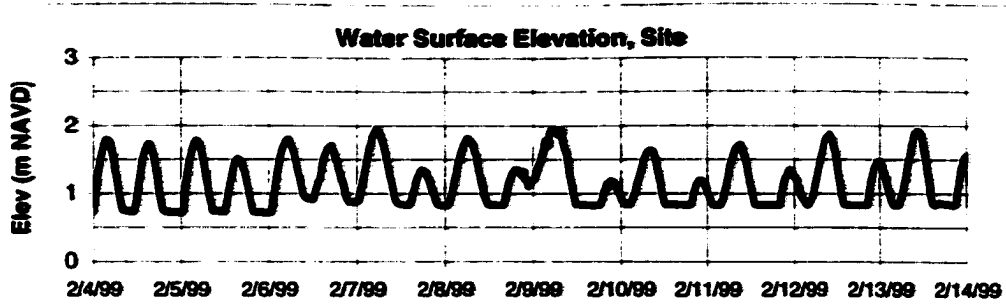
App B (5-23-02).xls: 36

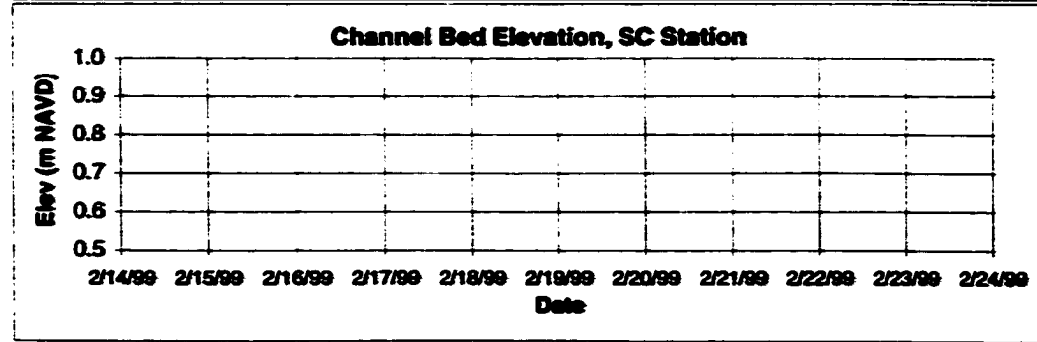
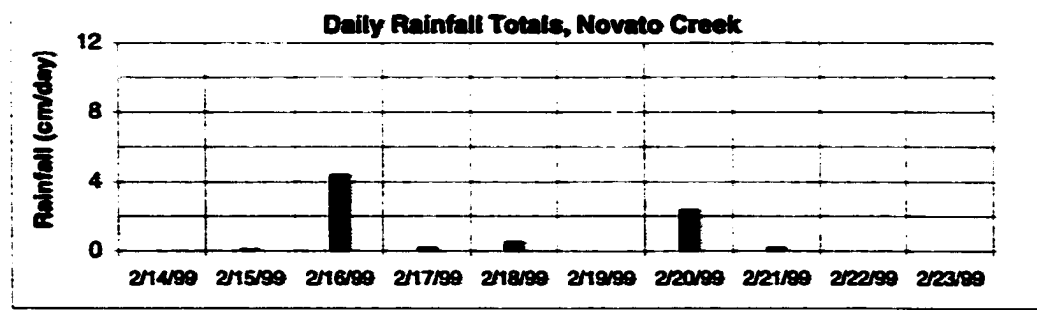
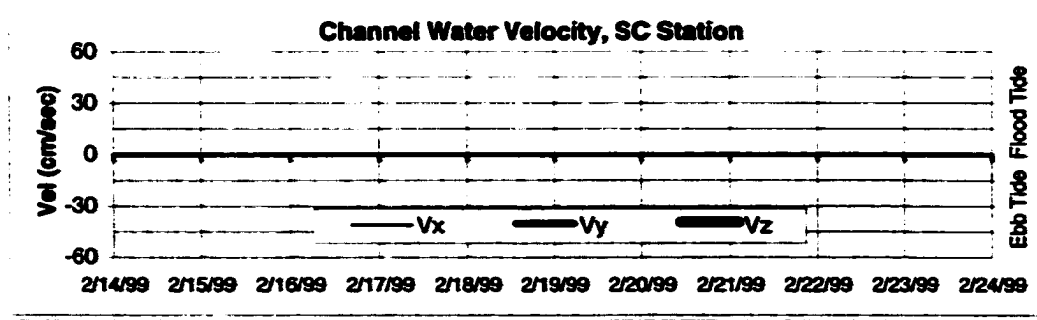
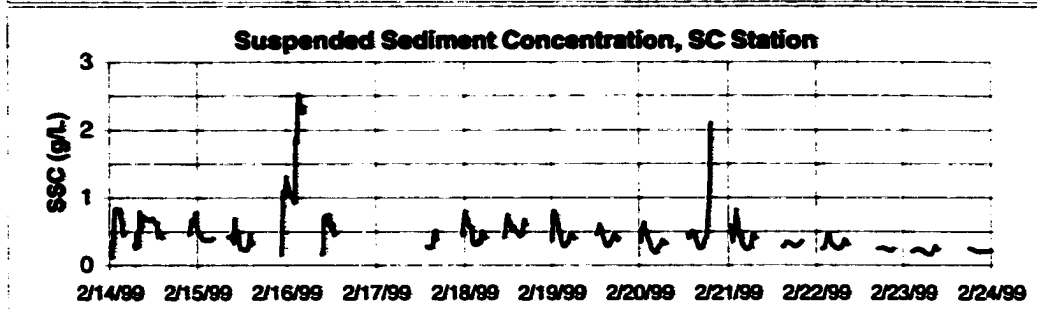
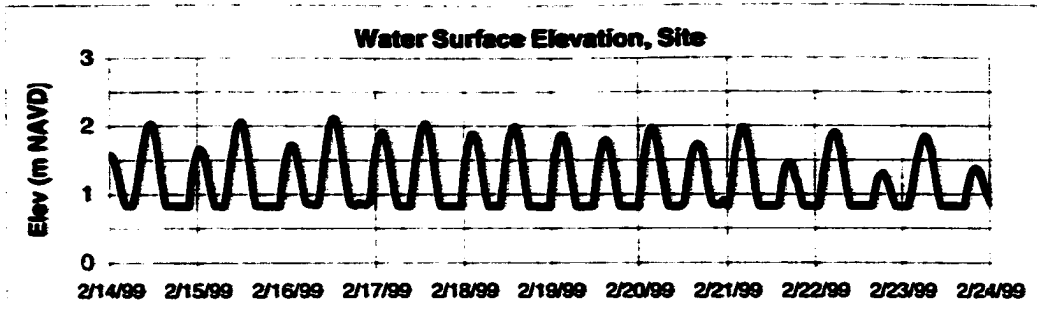


App B (5-23-02).xls: 37

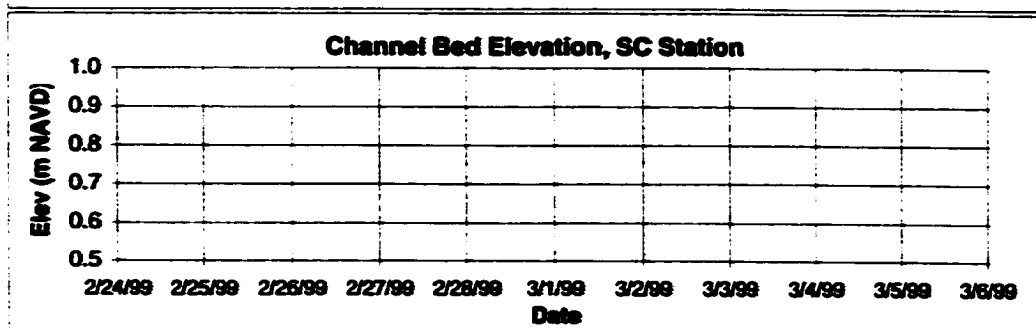
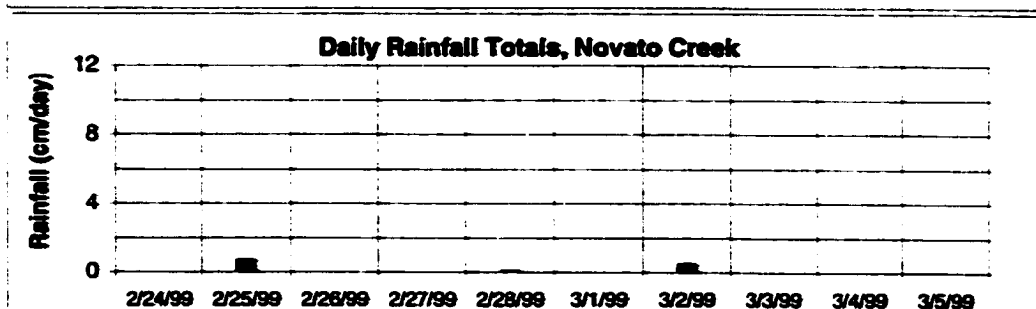
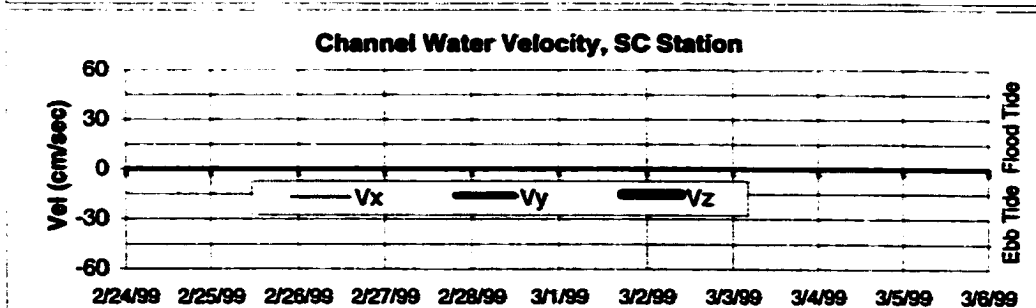
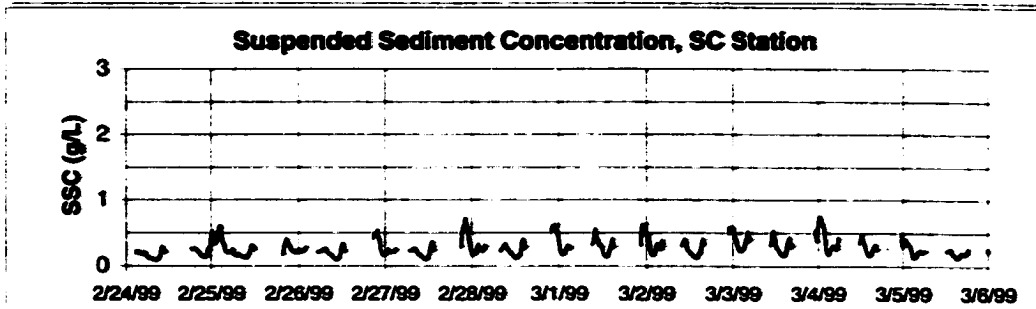
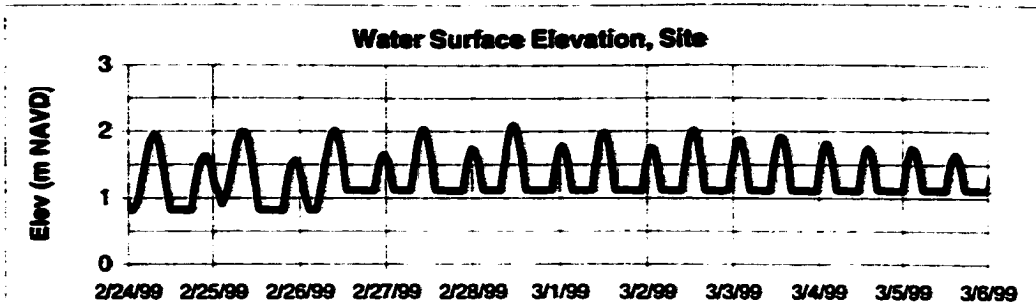


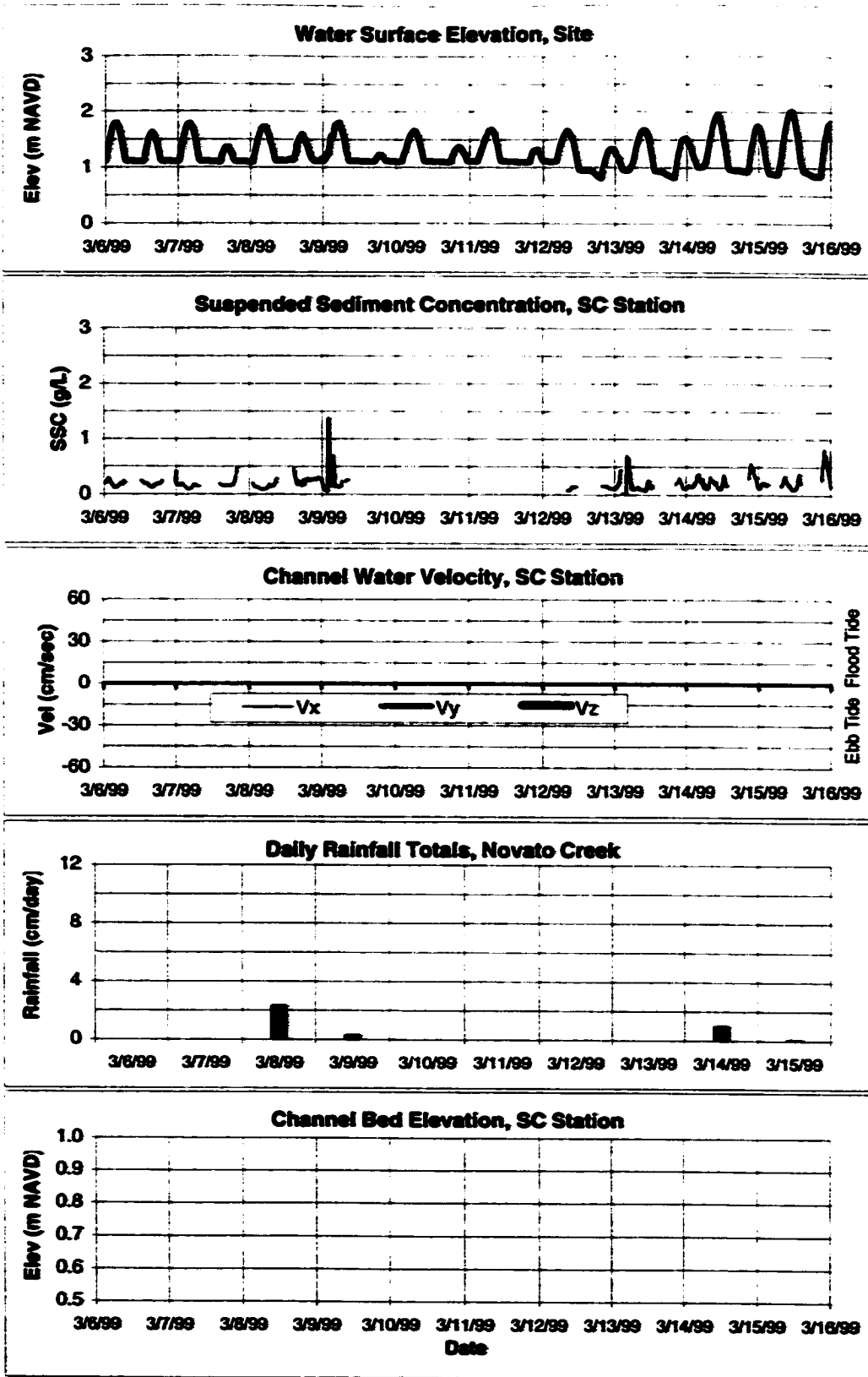
App B (5-23-02).xls: 38



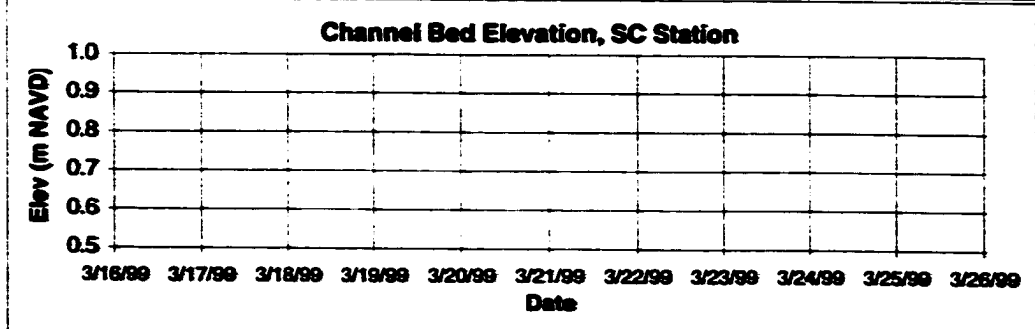
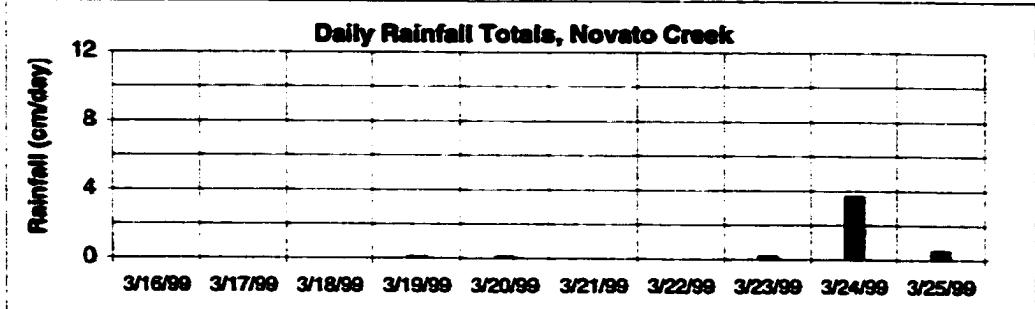
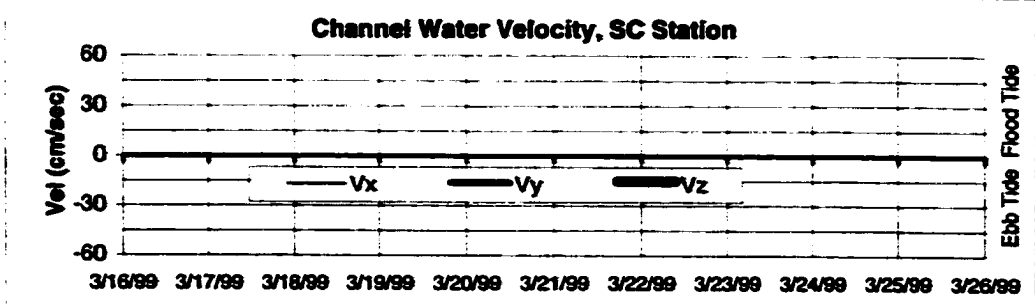
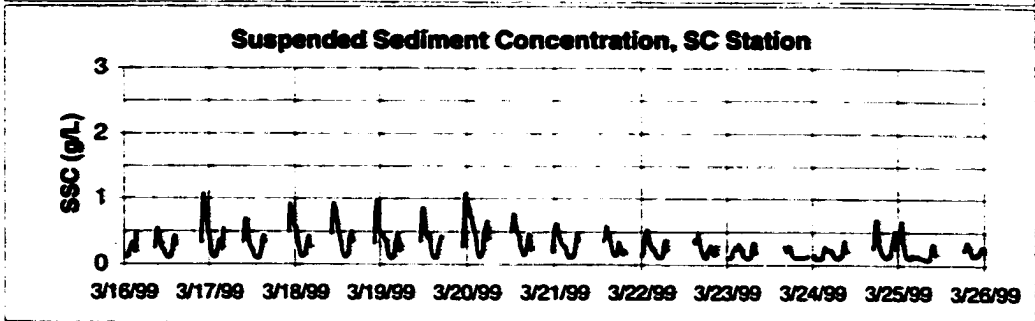
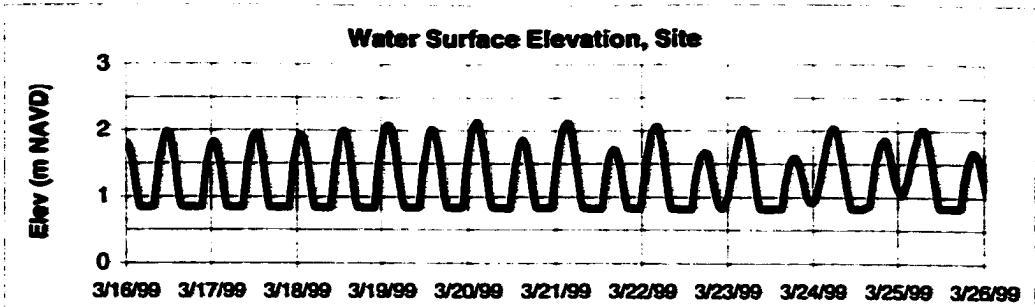


App B (5-23-02).xls: 40

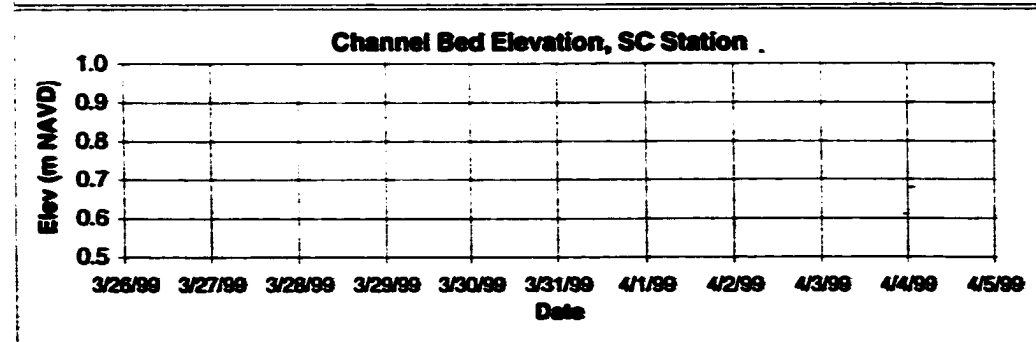
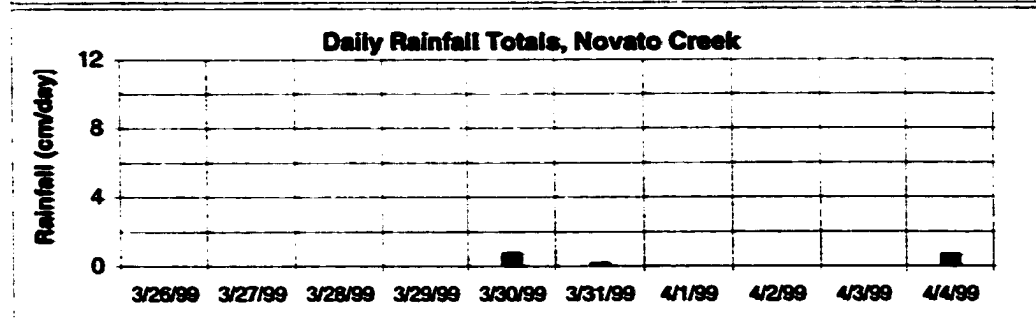
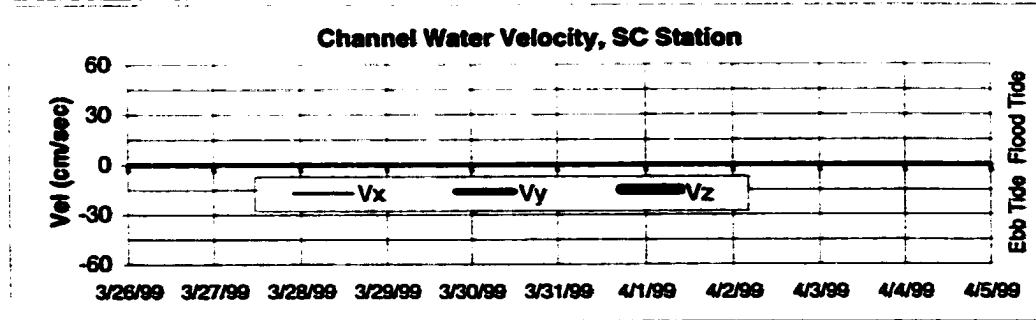
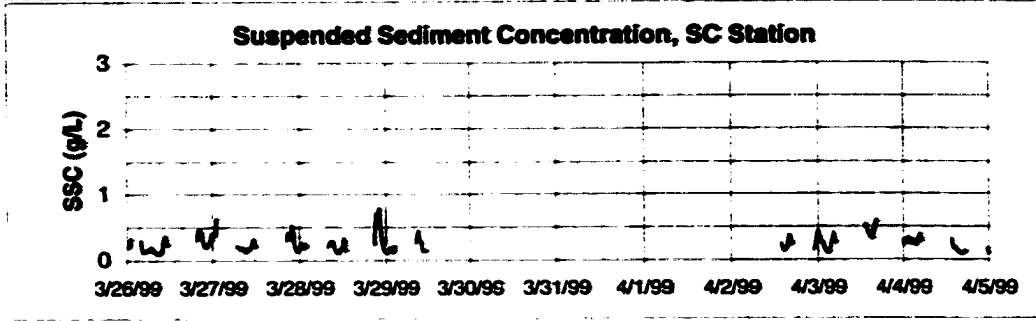
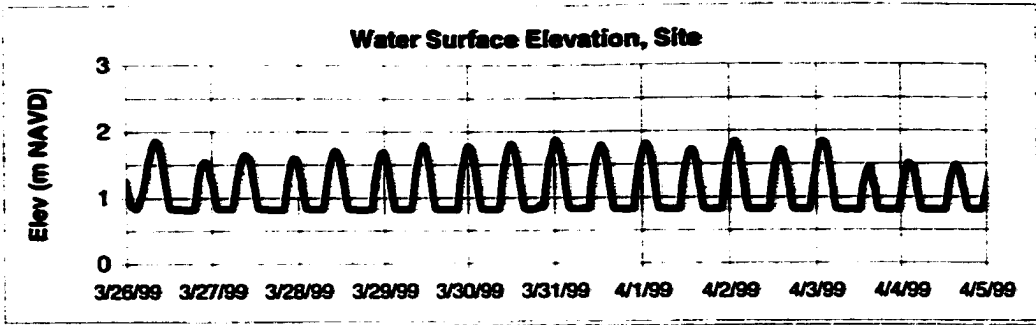




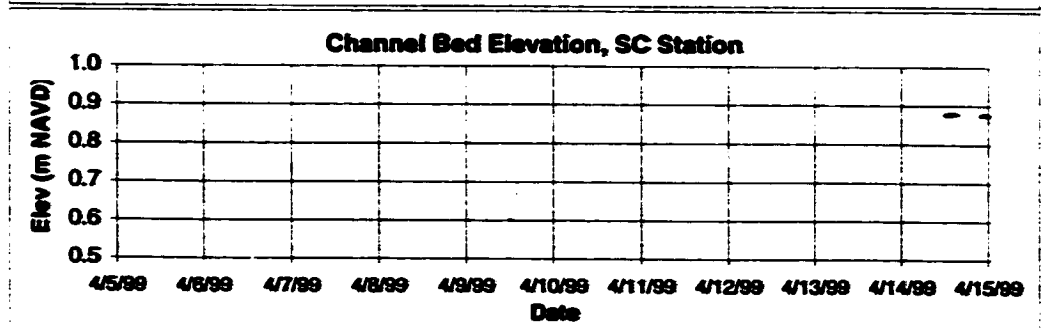
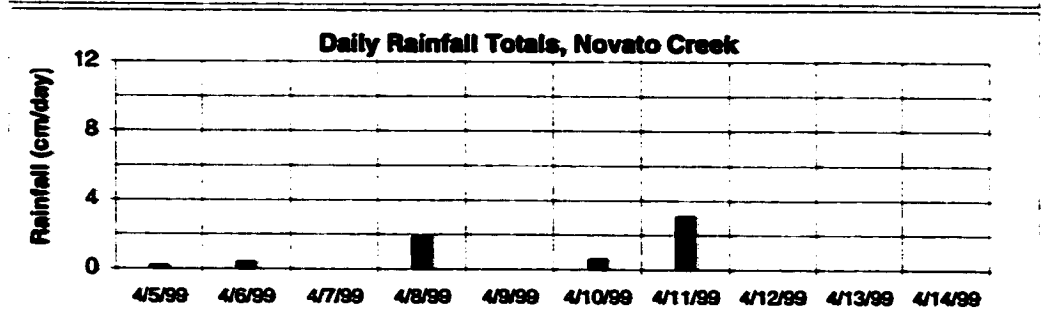
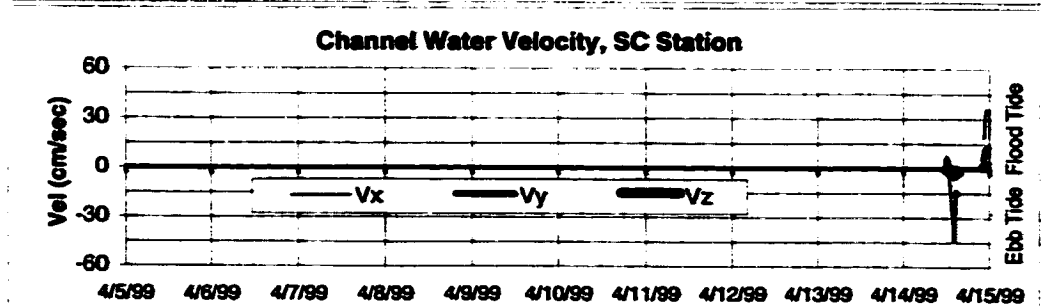
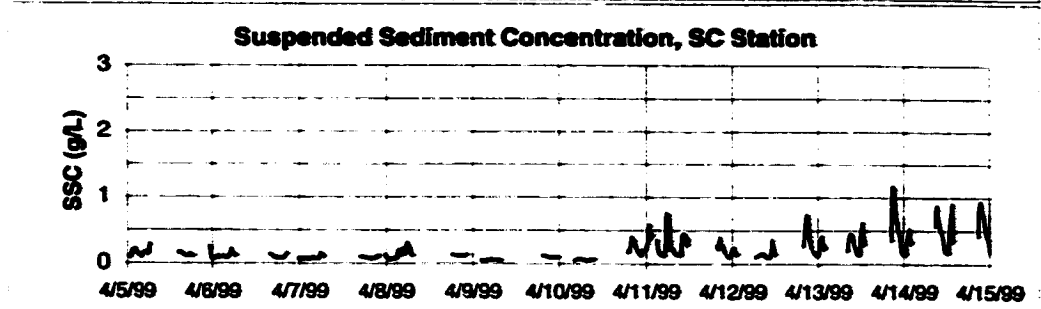
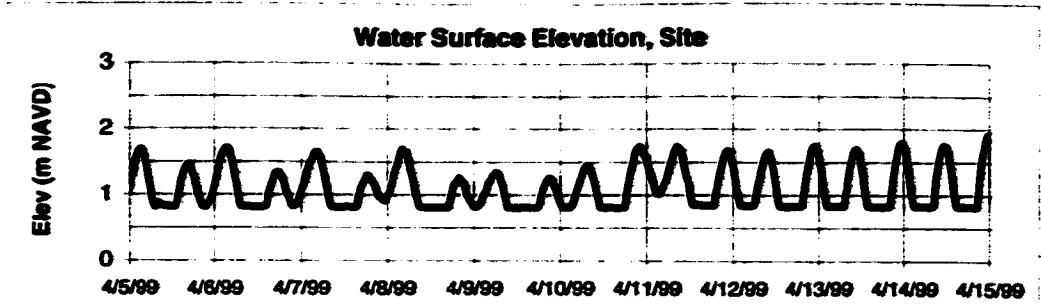
App B (5-23-02).xls: 42



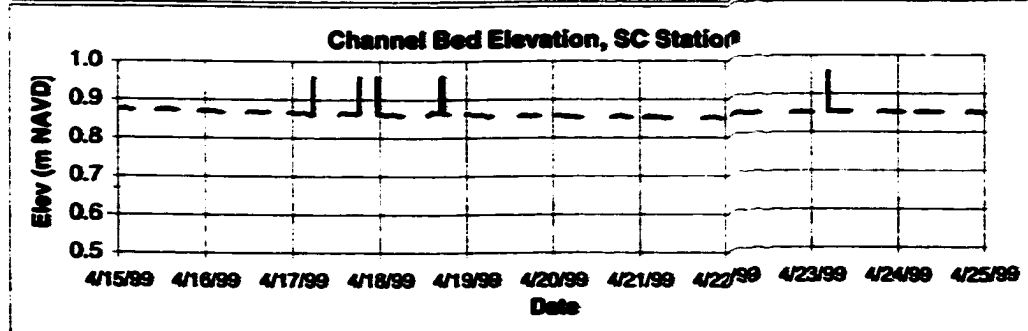
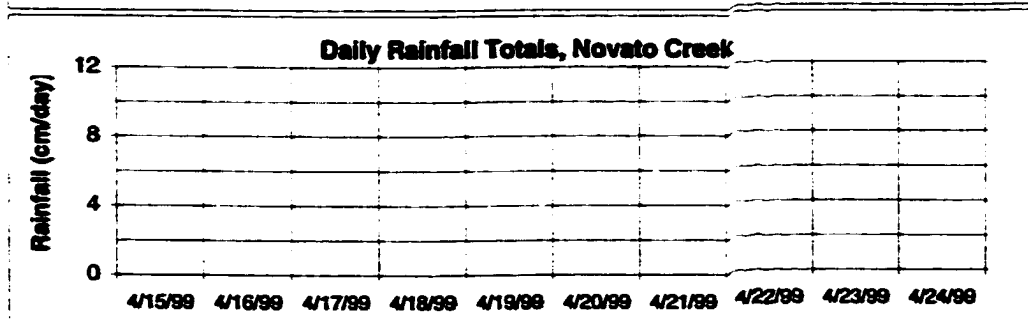
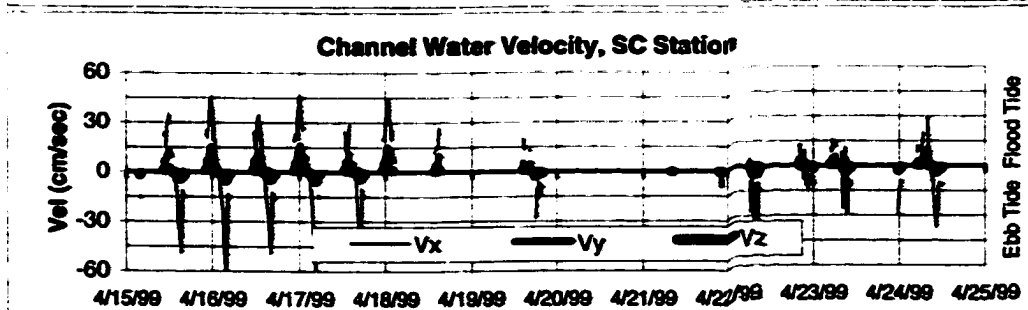
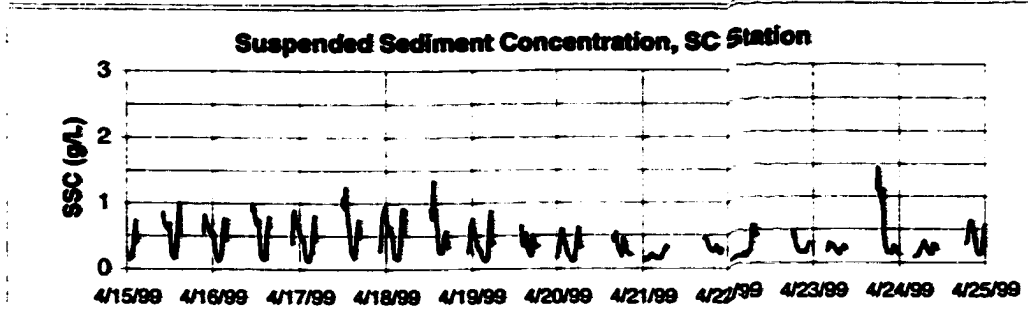
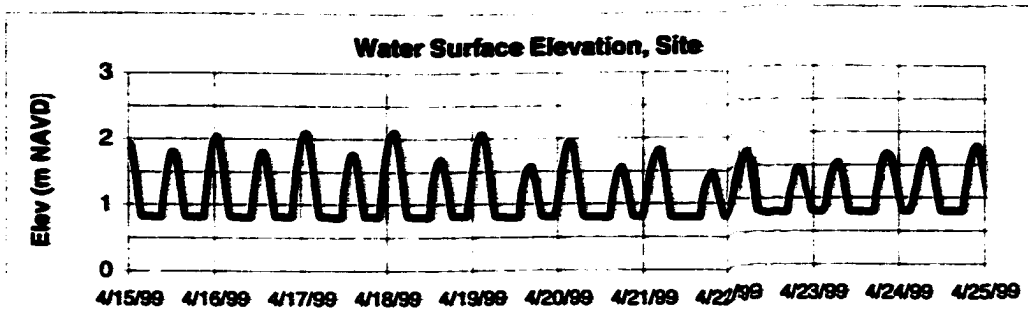
App B (5-23-02).xls: 43



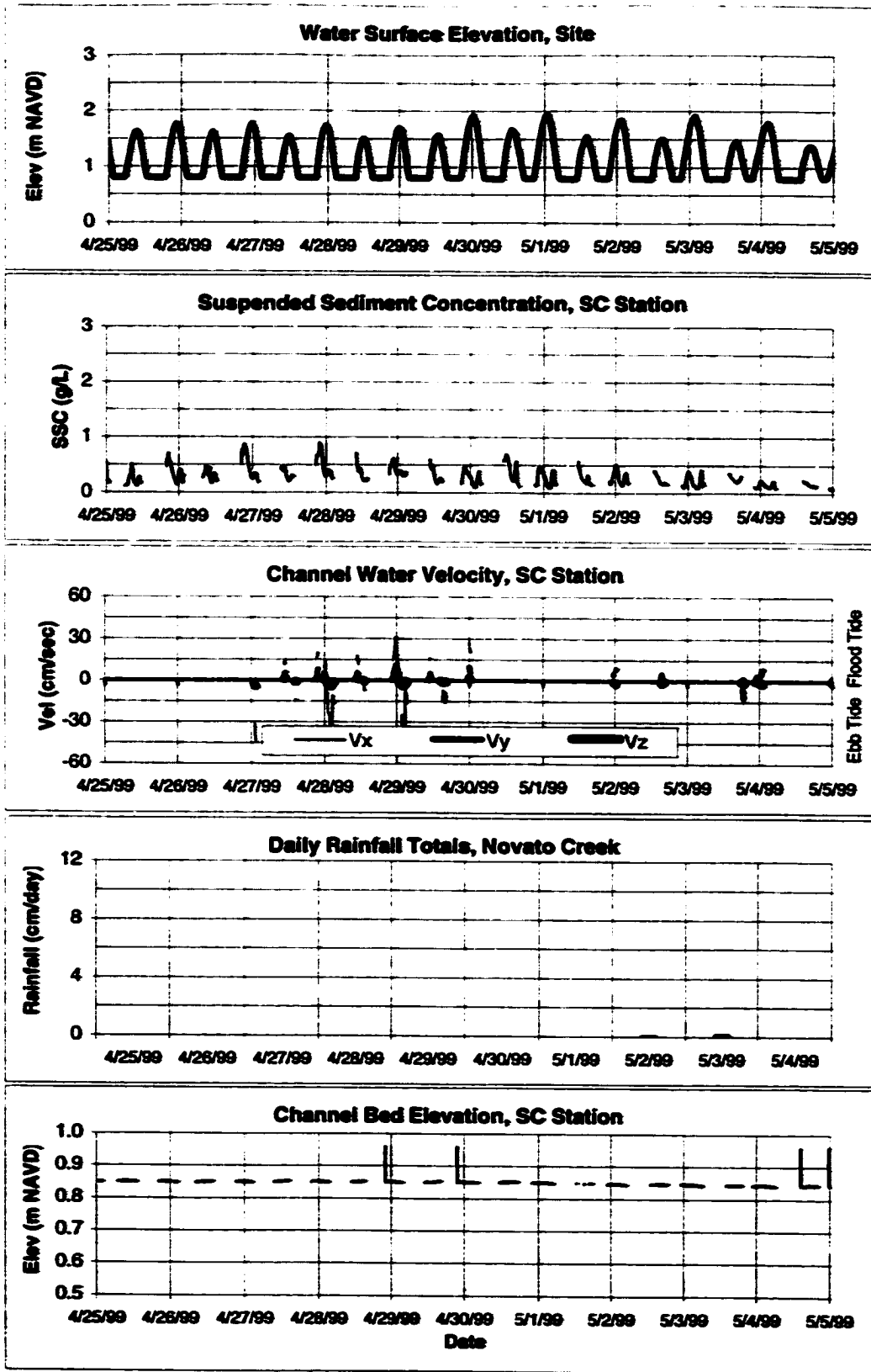
App B (5-23-02).xls: 44



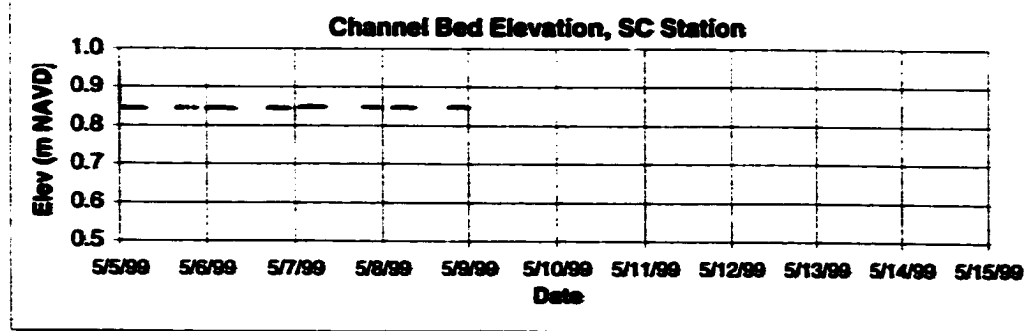
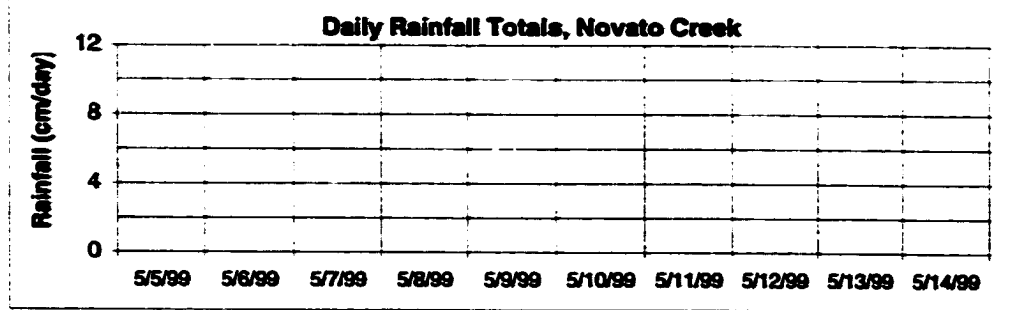
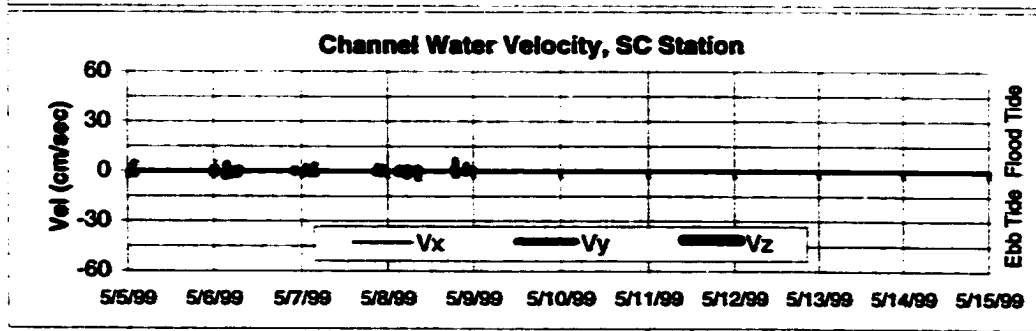
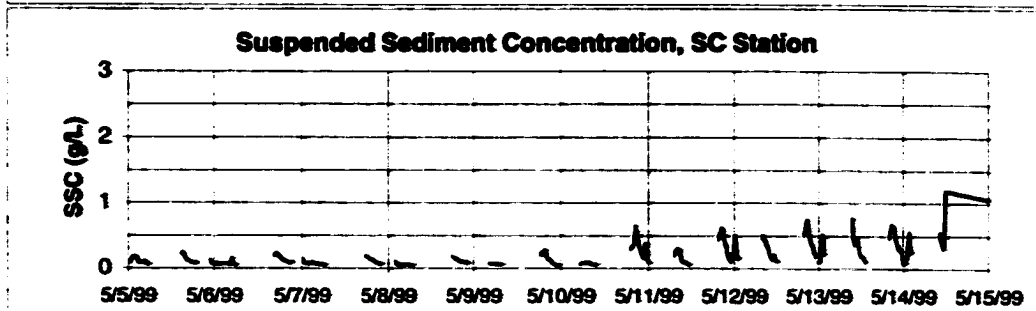
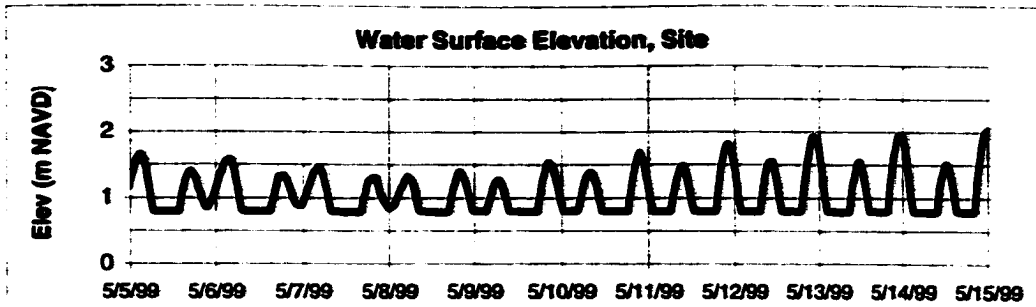
App B (5-23-02).doc 45



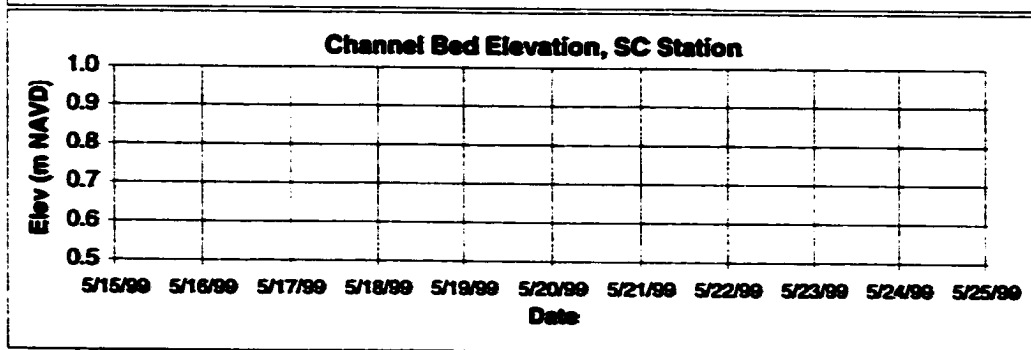
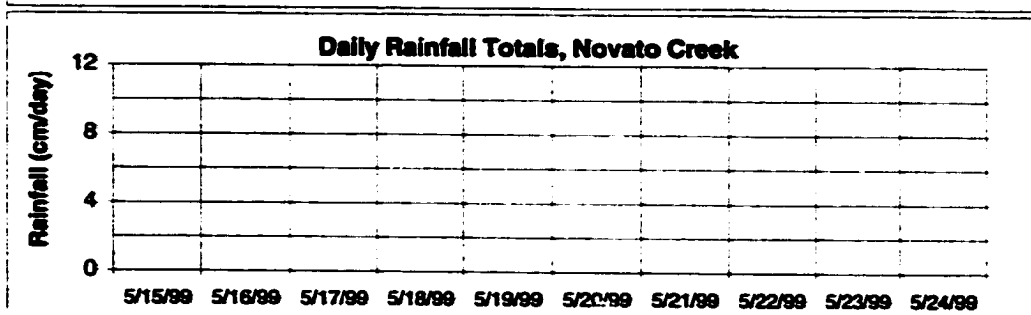
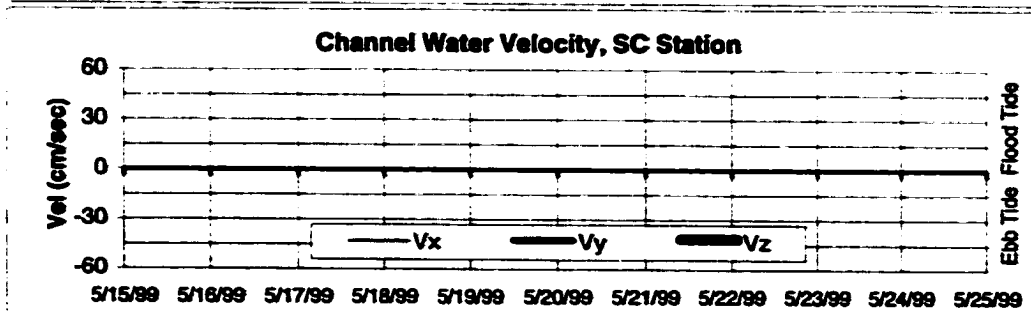
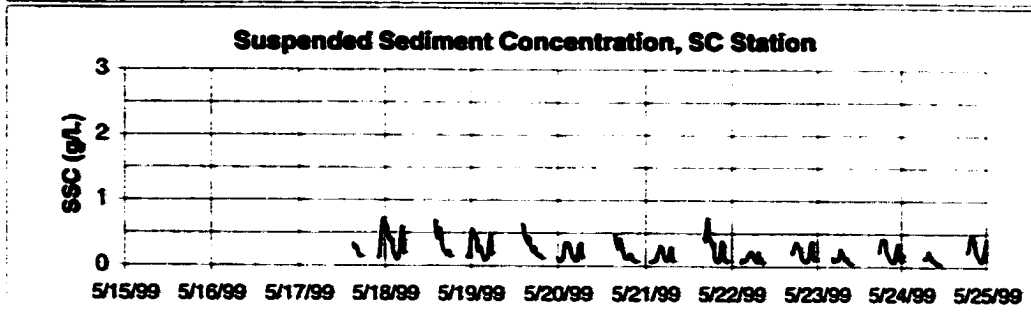
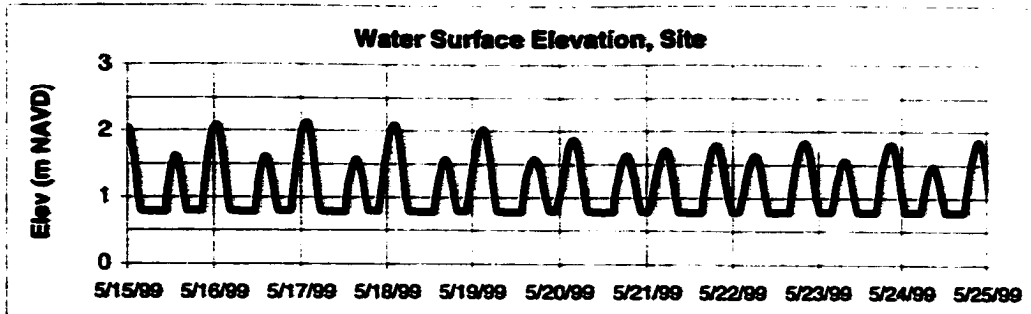
App B (5-23-02).xls: 46



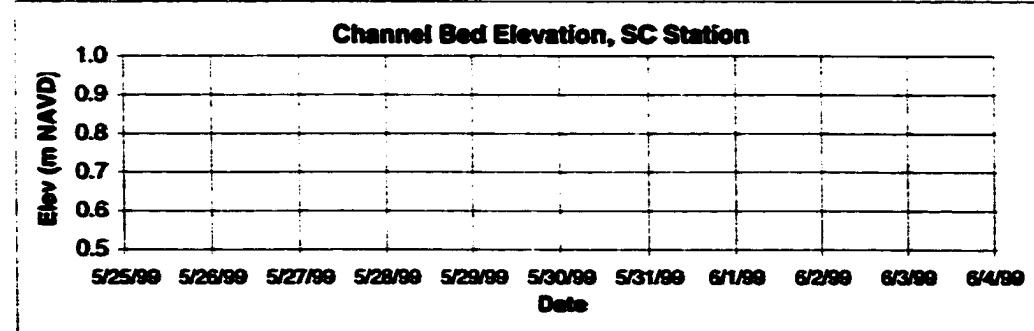
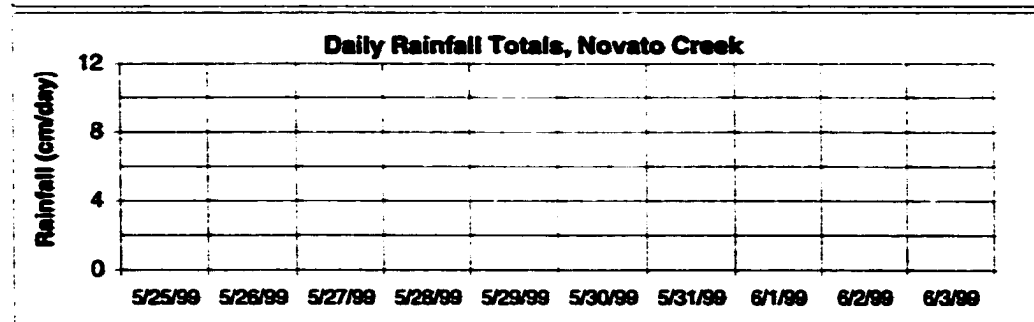
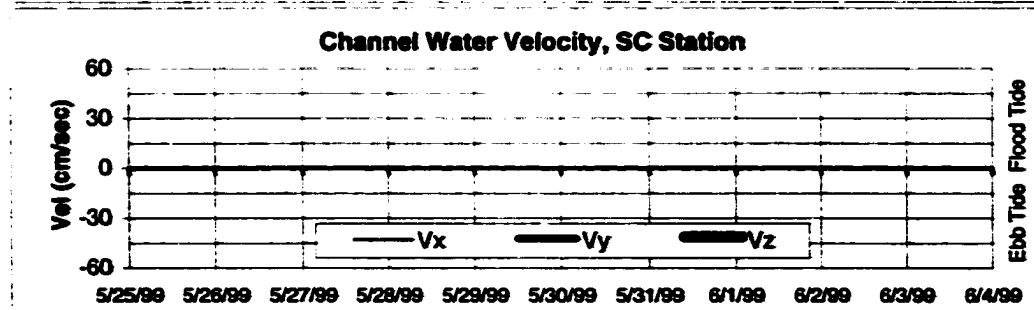
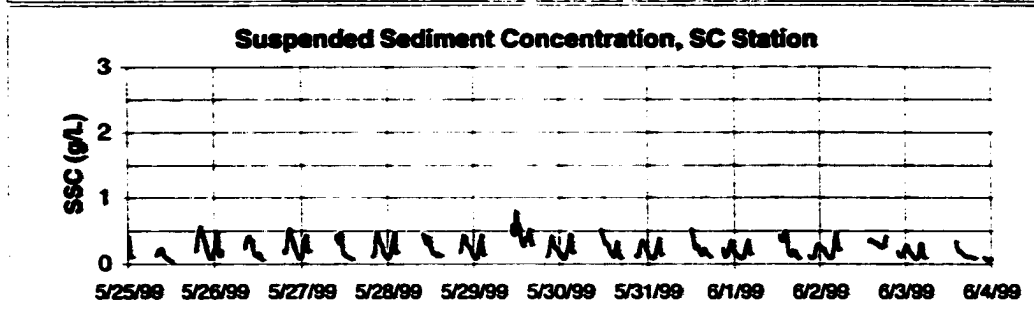
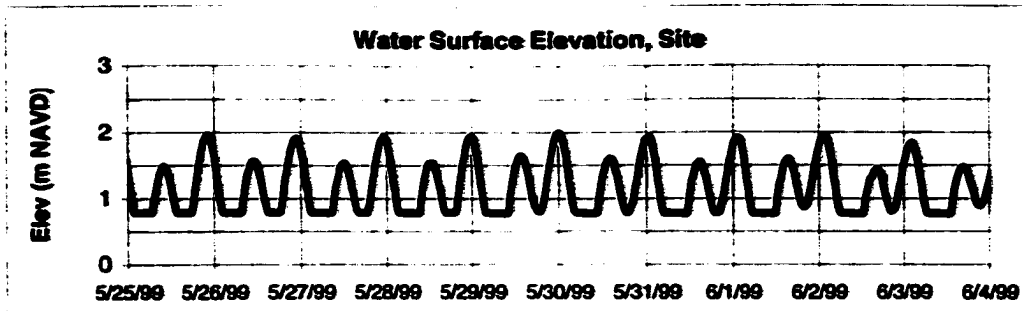
App B (5-23-02).xls: 47



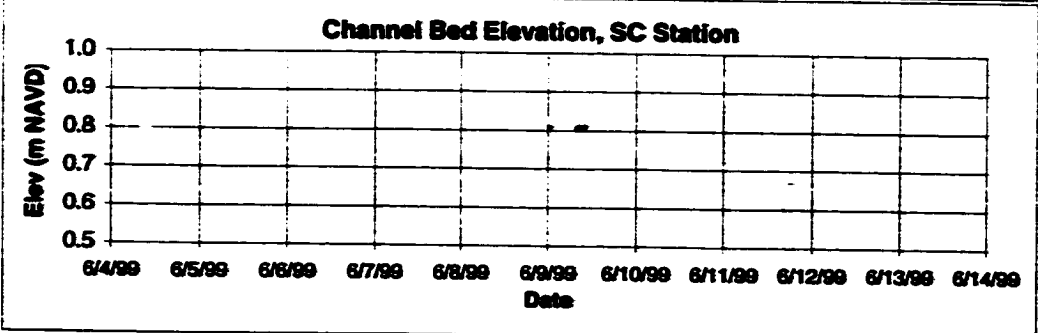
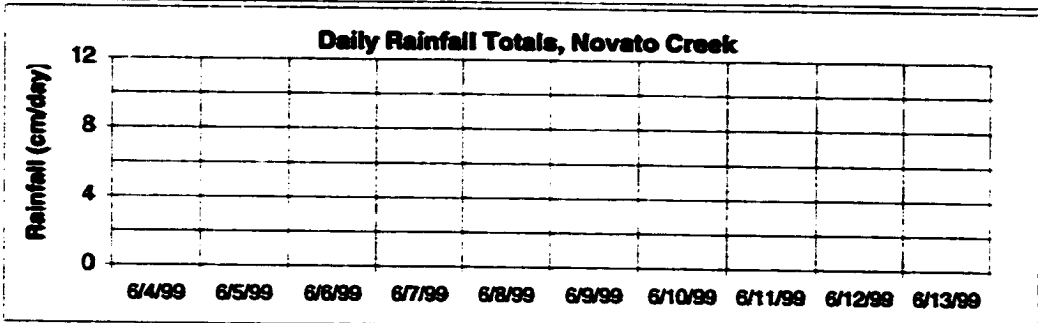
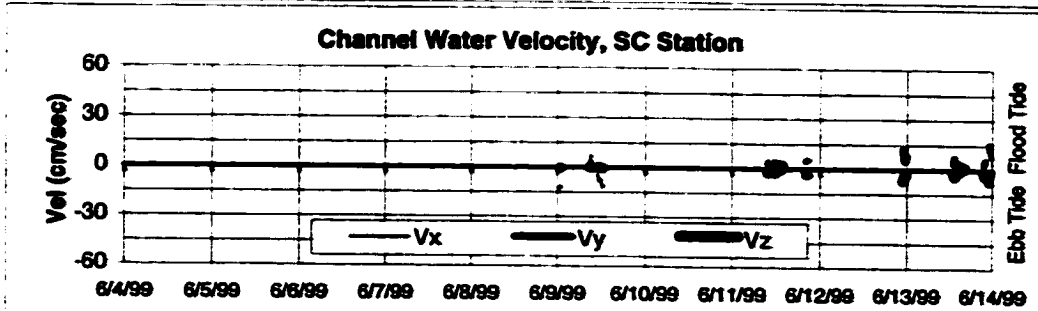
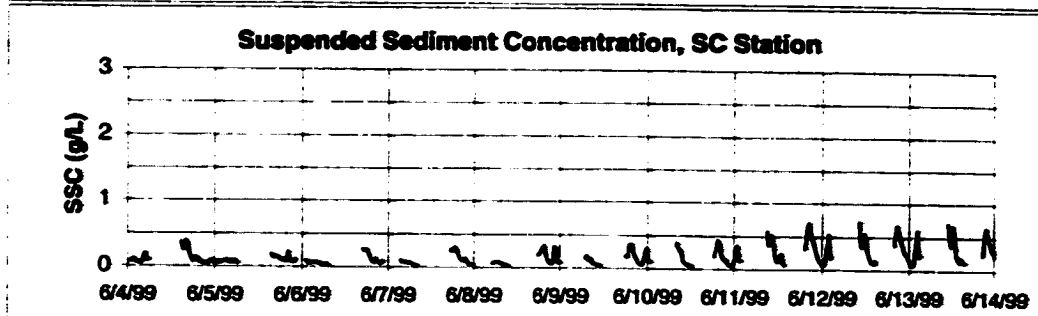
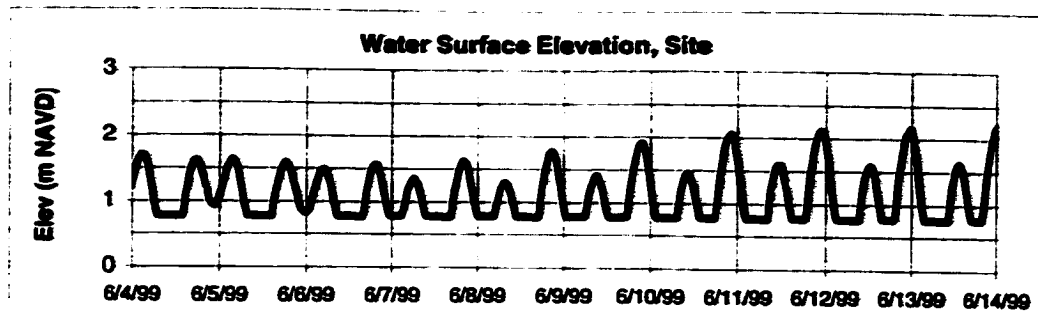
App B (5-23-02).xls: 48



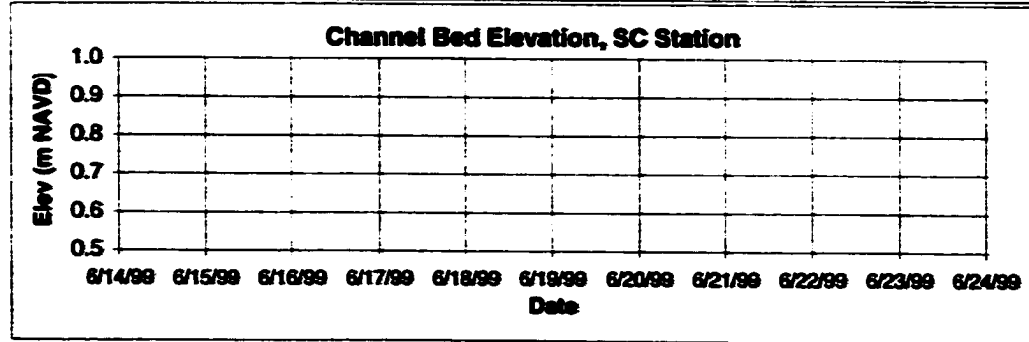
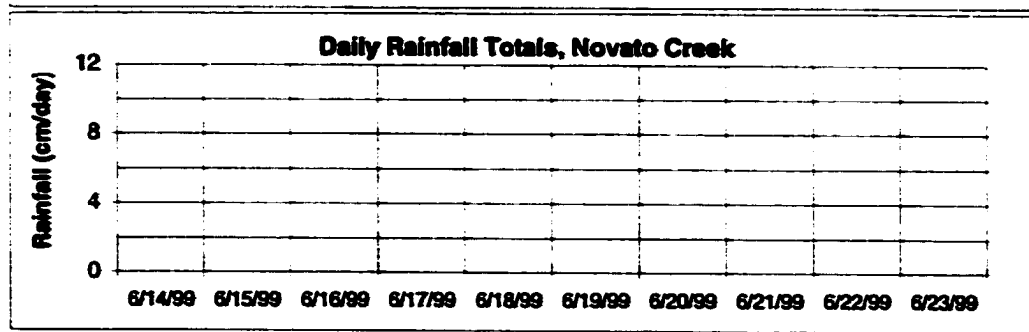
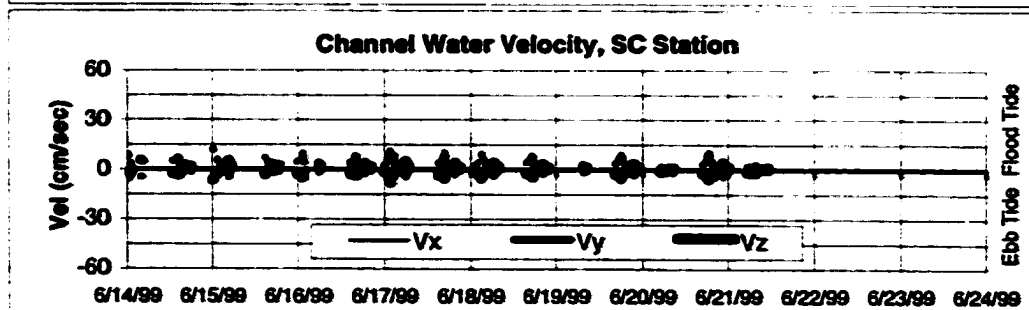
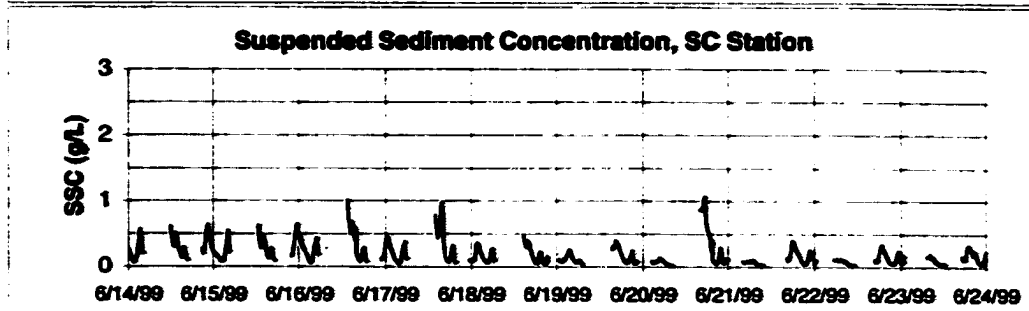
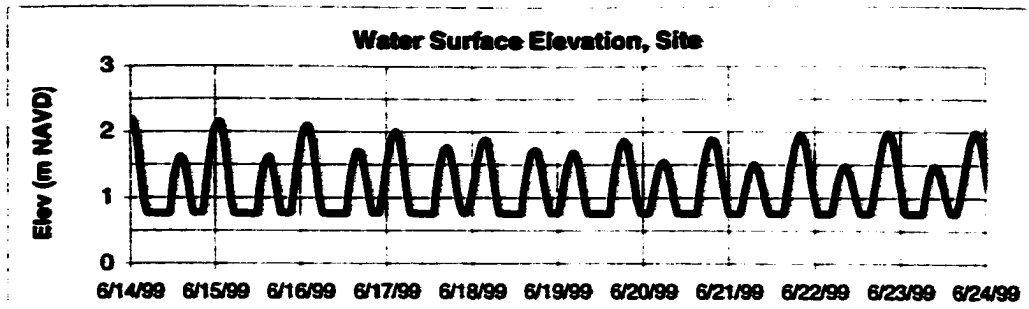
App B (5-23-02).xls: 49

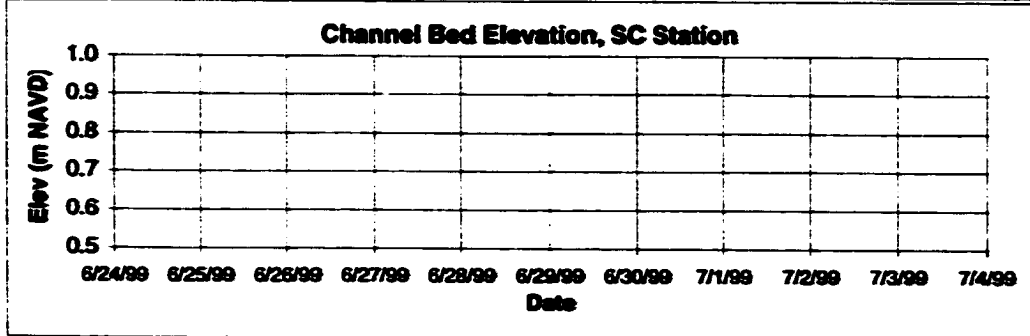
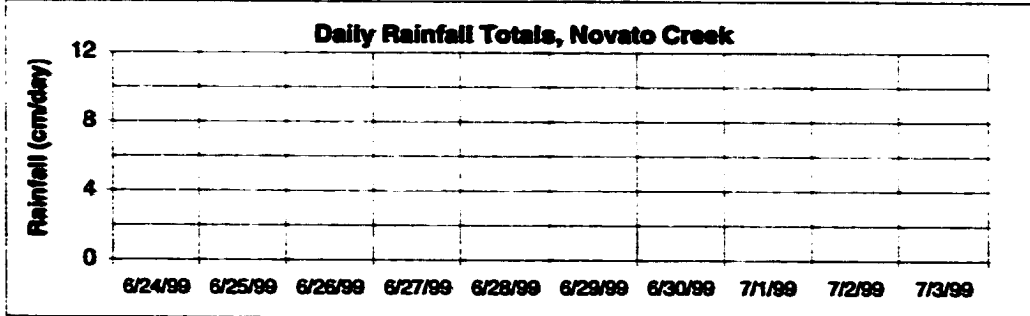
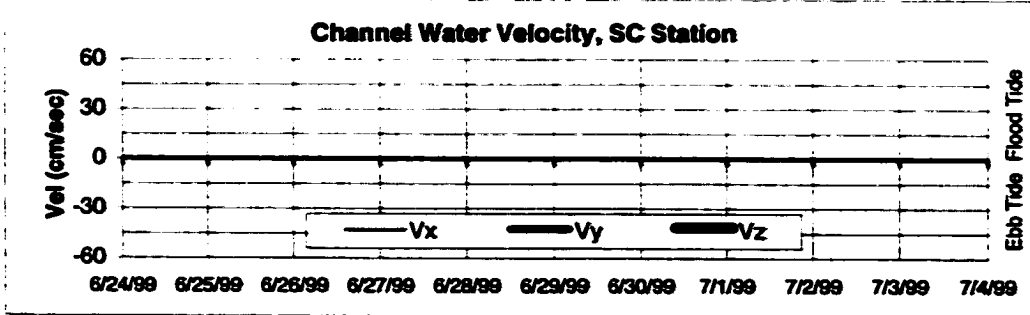
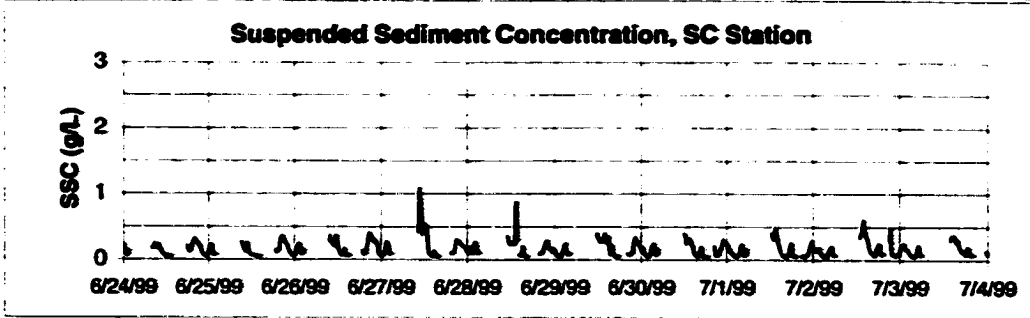
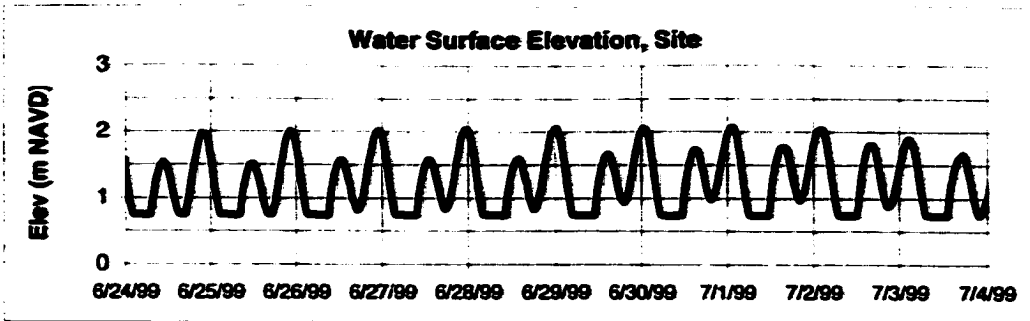


App B (5-23-02).xls: 50

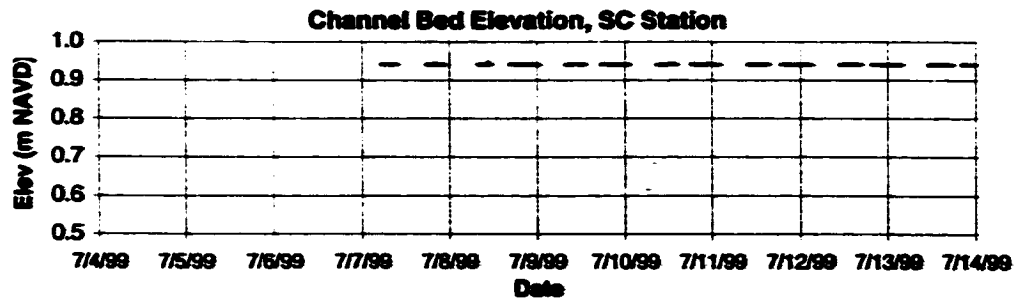
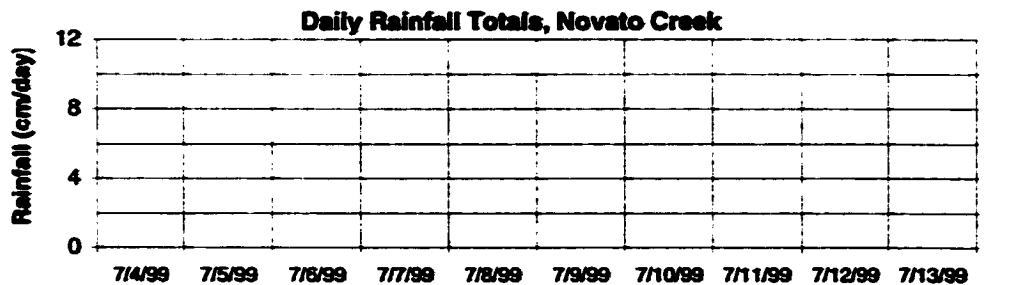
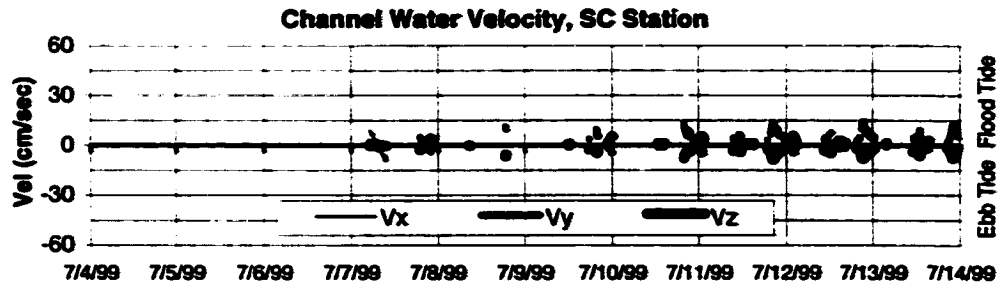
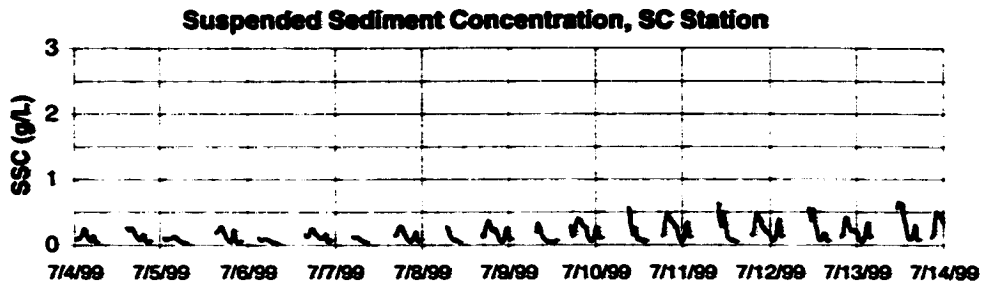
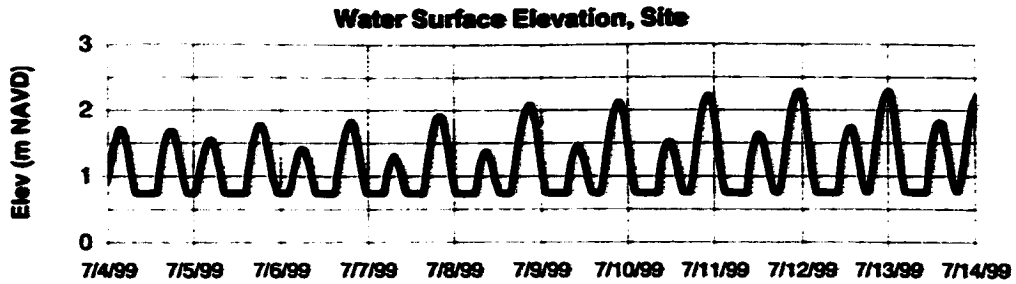


App B (5-23-02).xls: 51

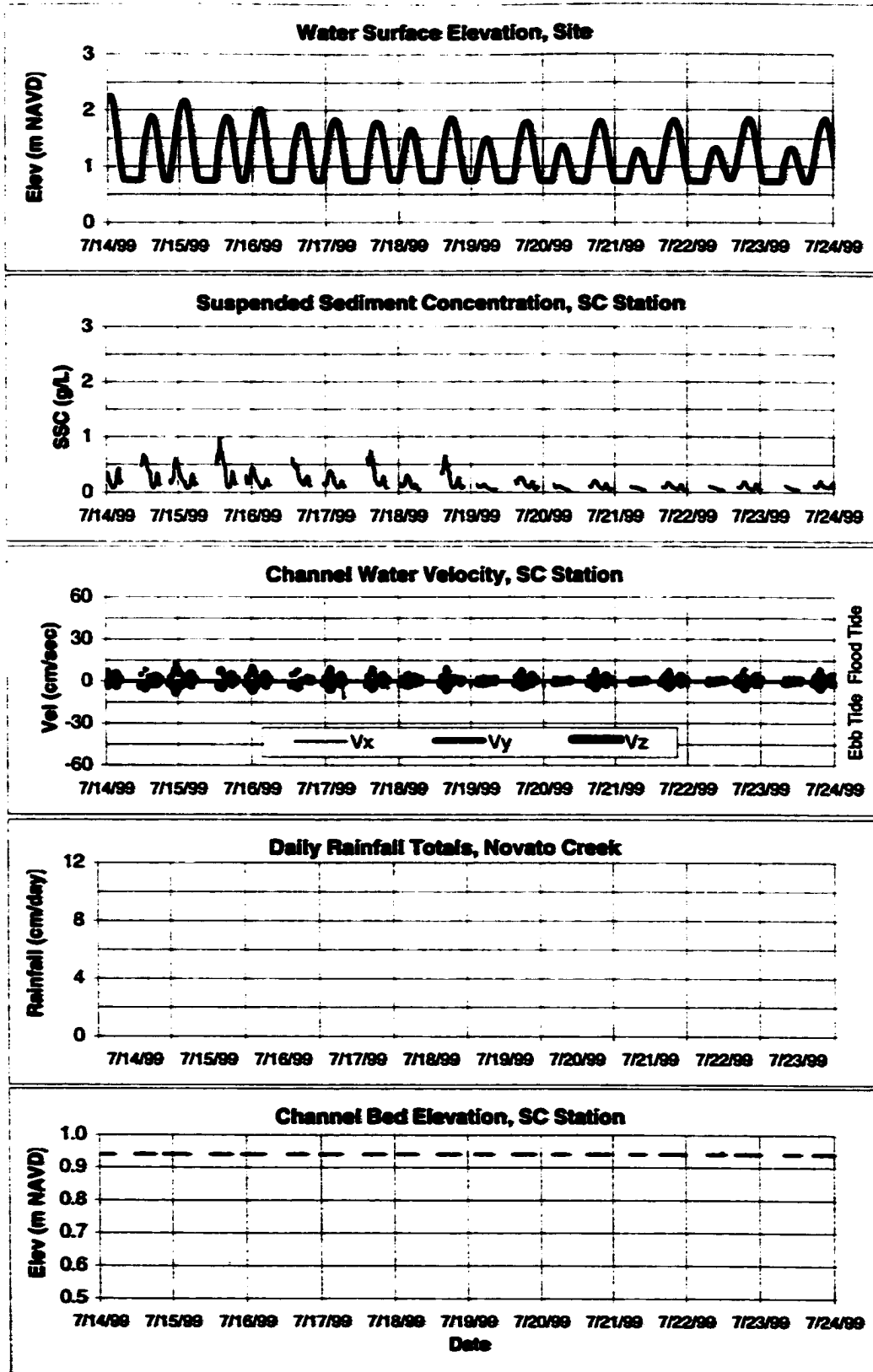




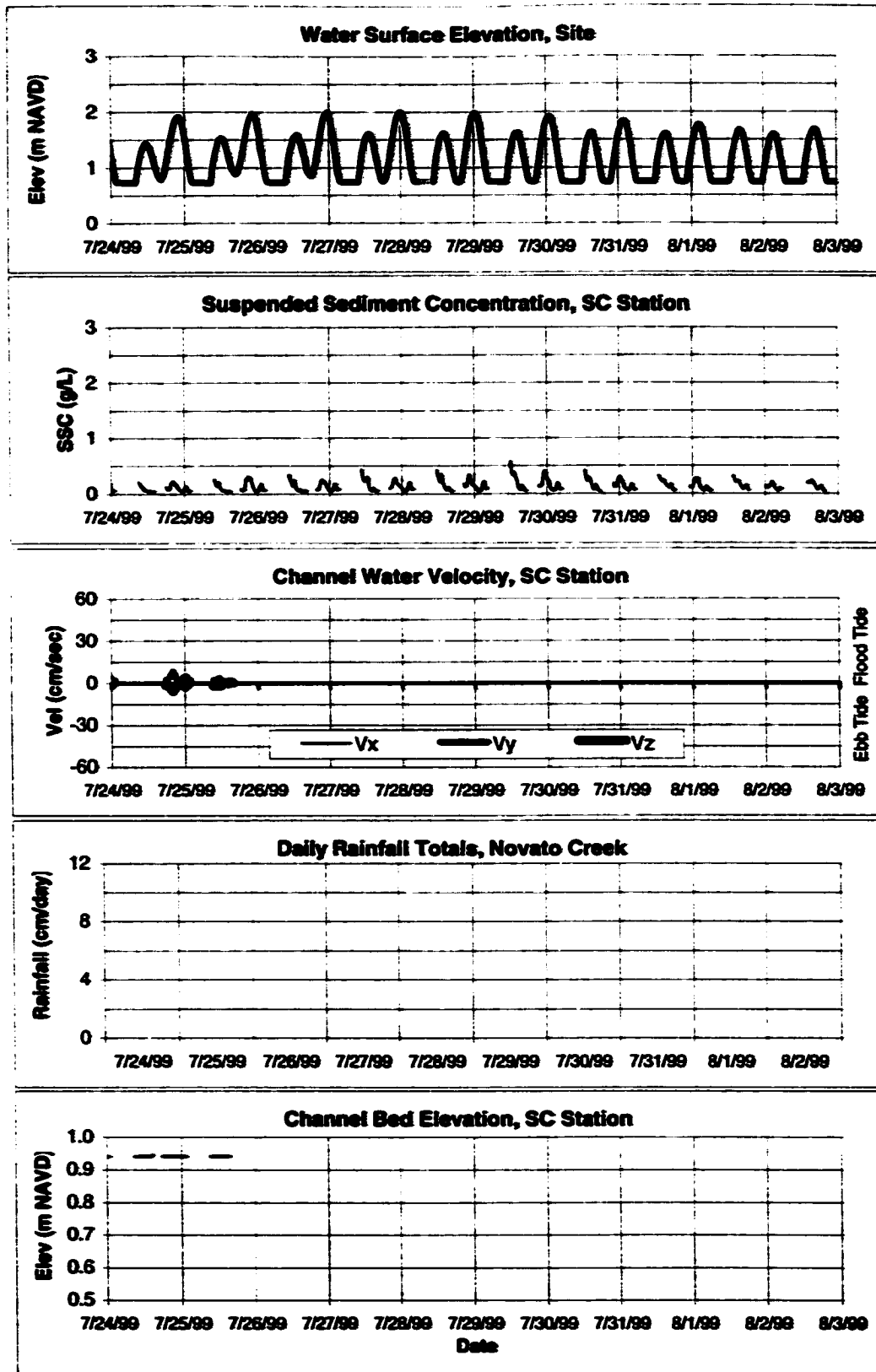
App B (5-23-02).xls: 53



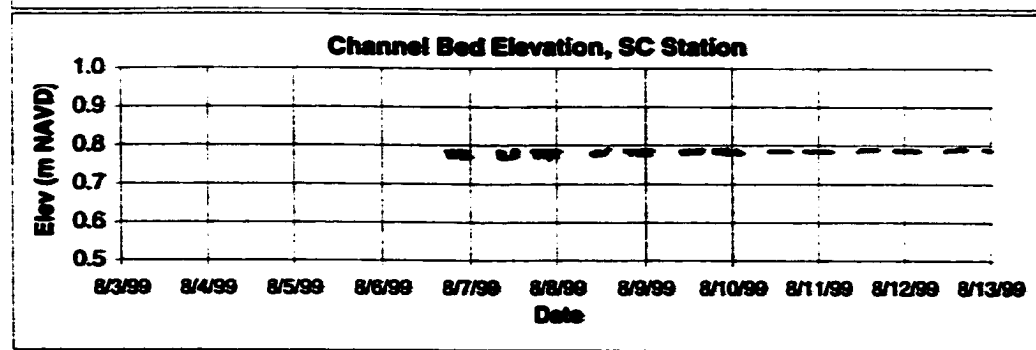
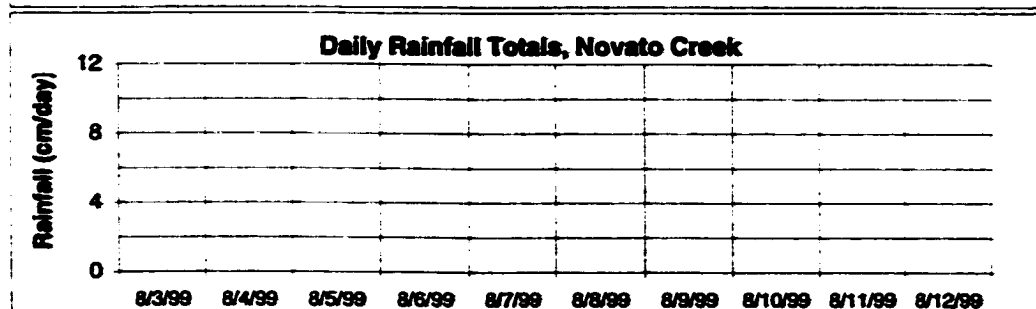
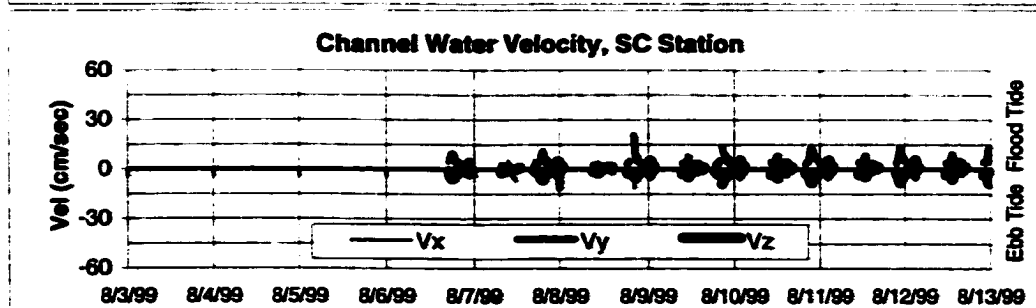
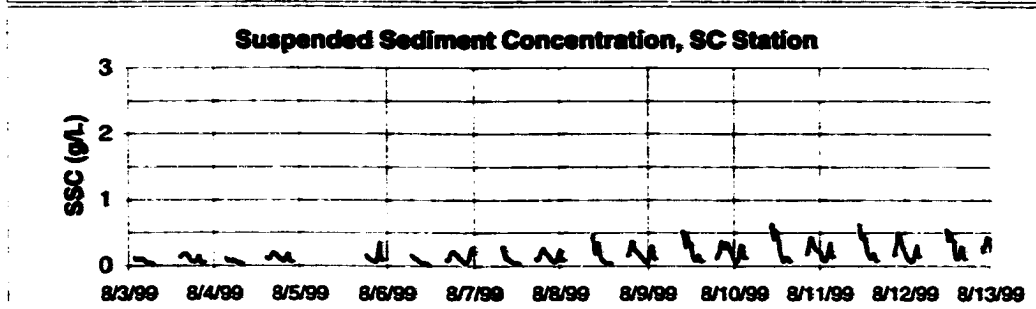
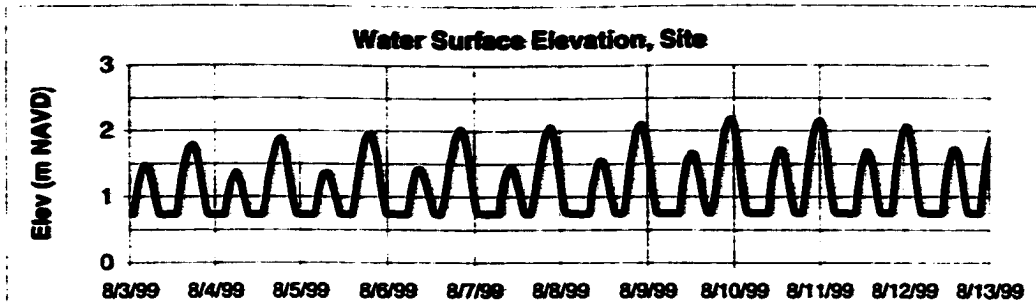
App B (5-23-02).xls: 54



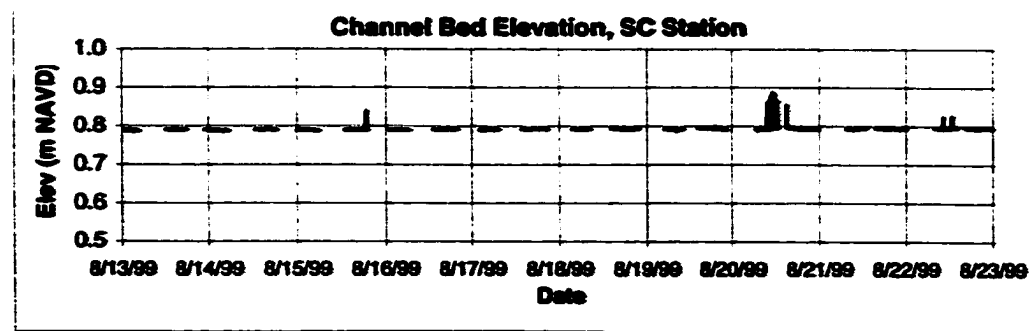
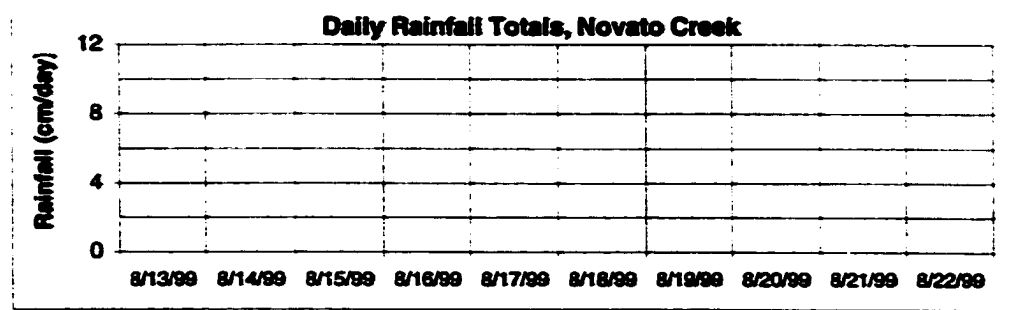
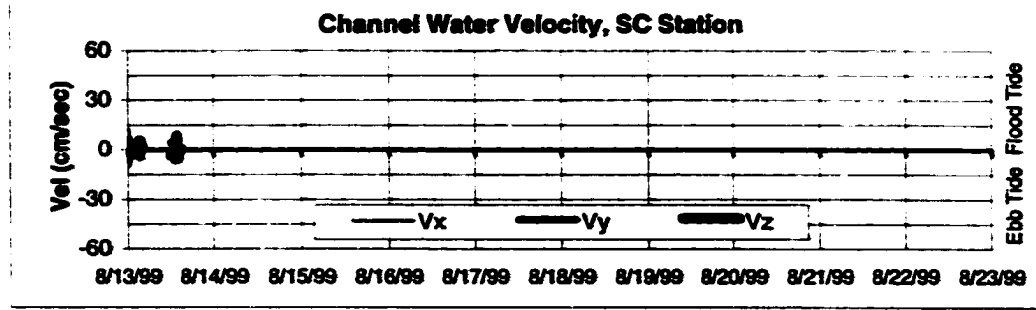
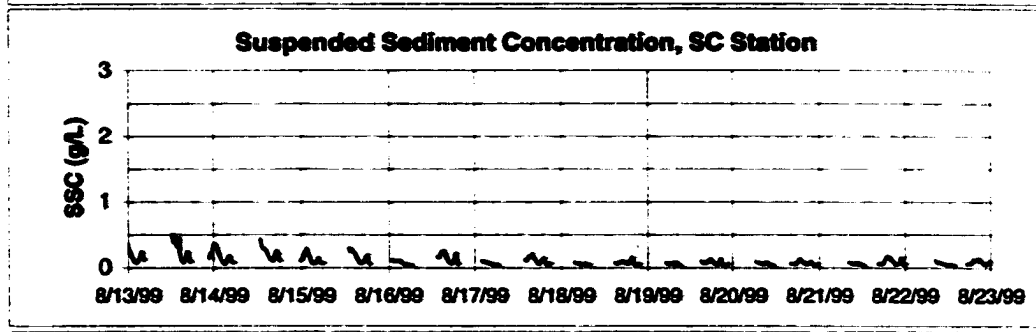
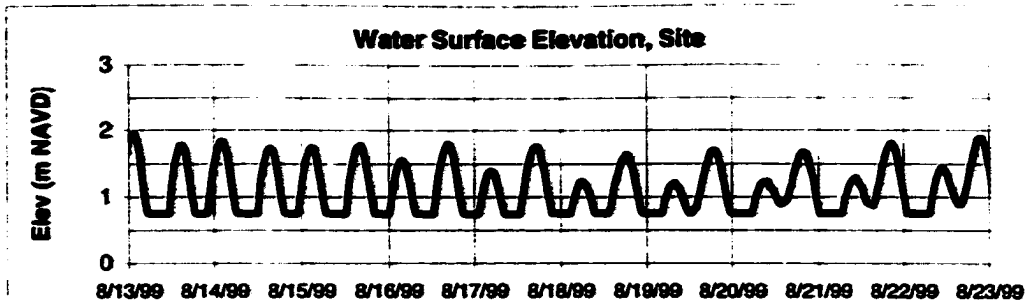
App B (5-23-02).xls: 55



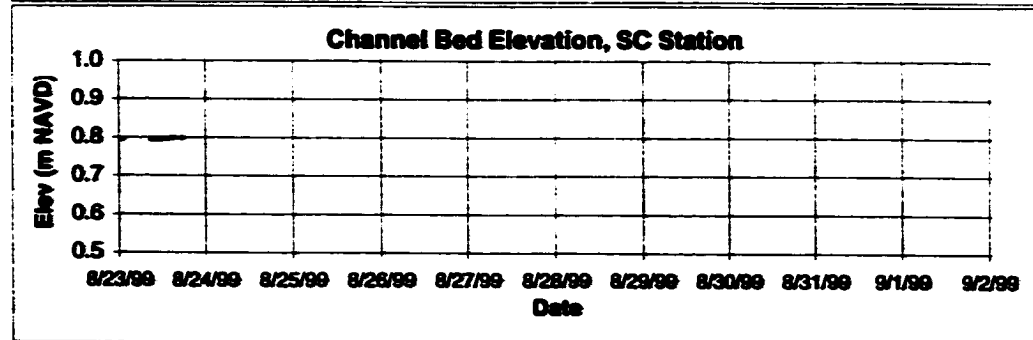
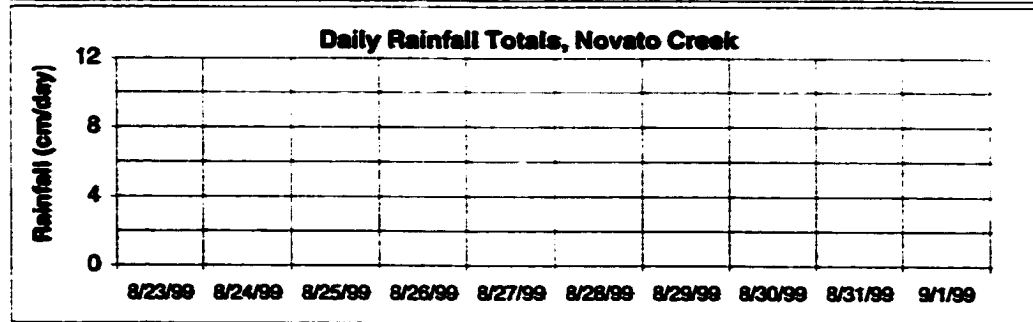
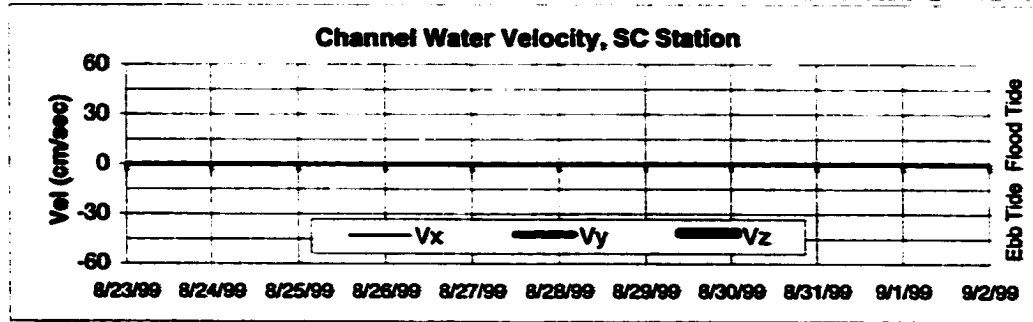
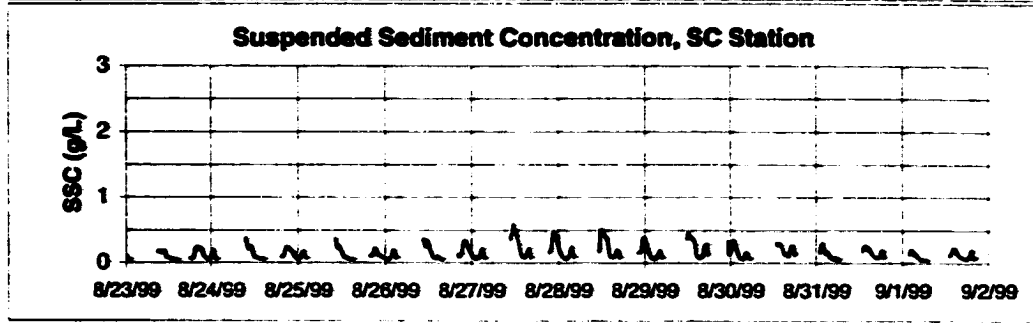
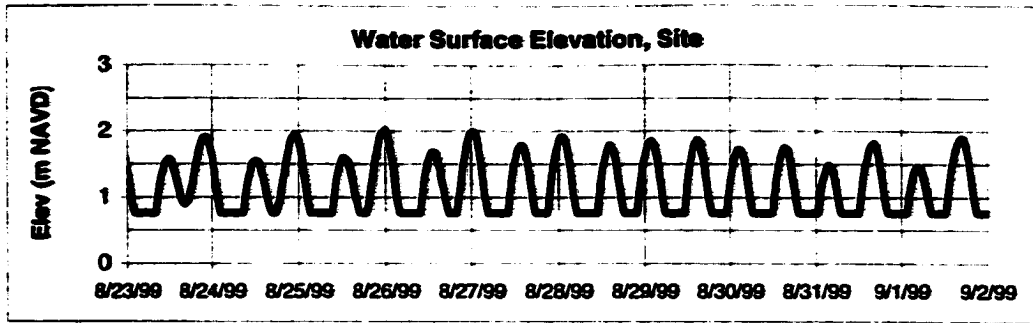
App B (5-23-02).xls: 56



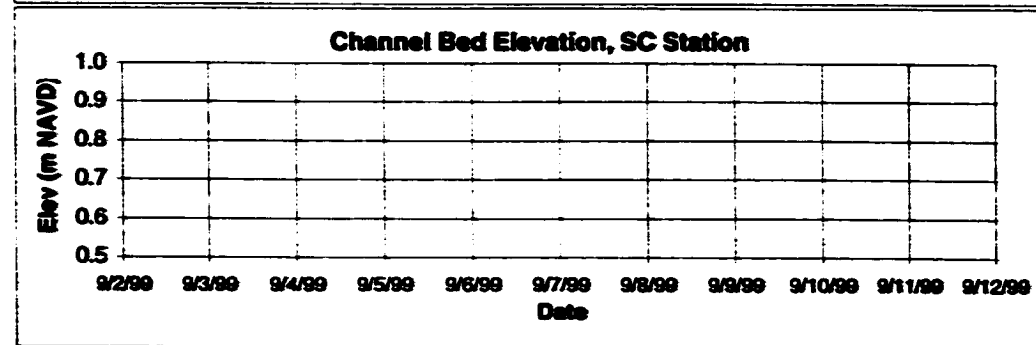
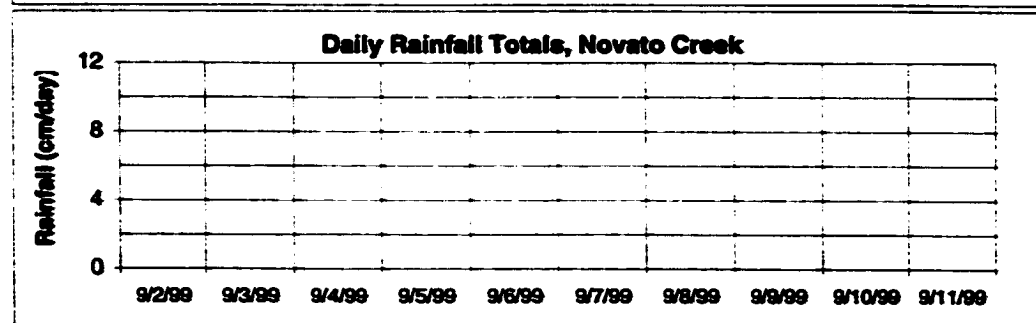
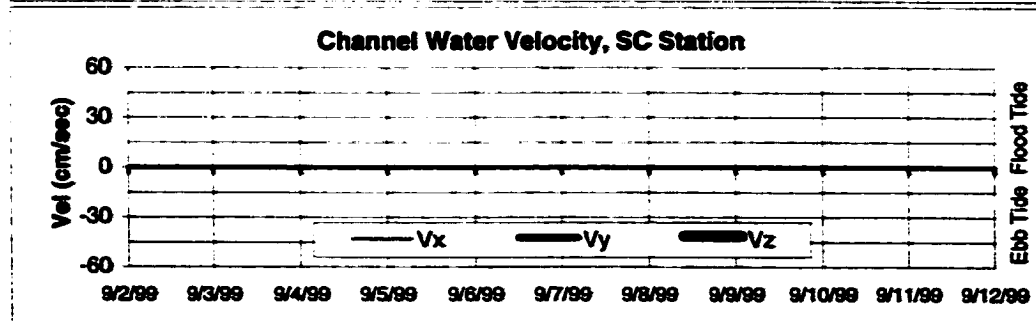
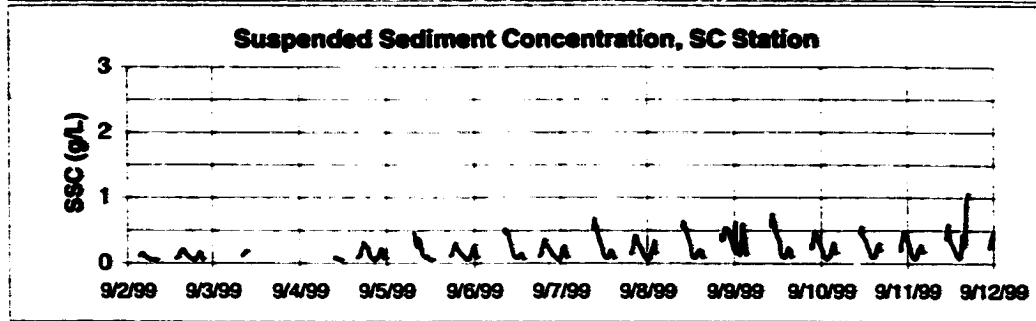
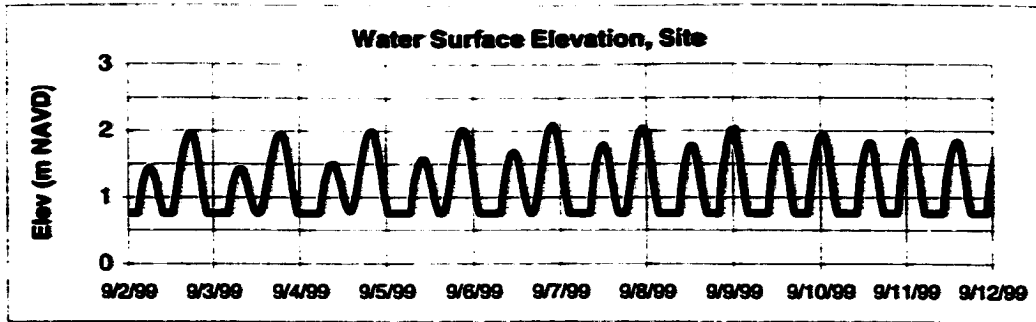
App B (5-23-02).xls: 57



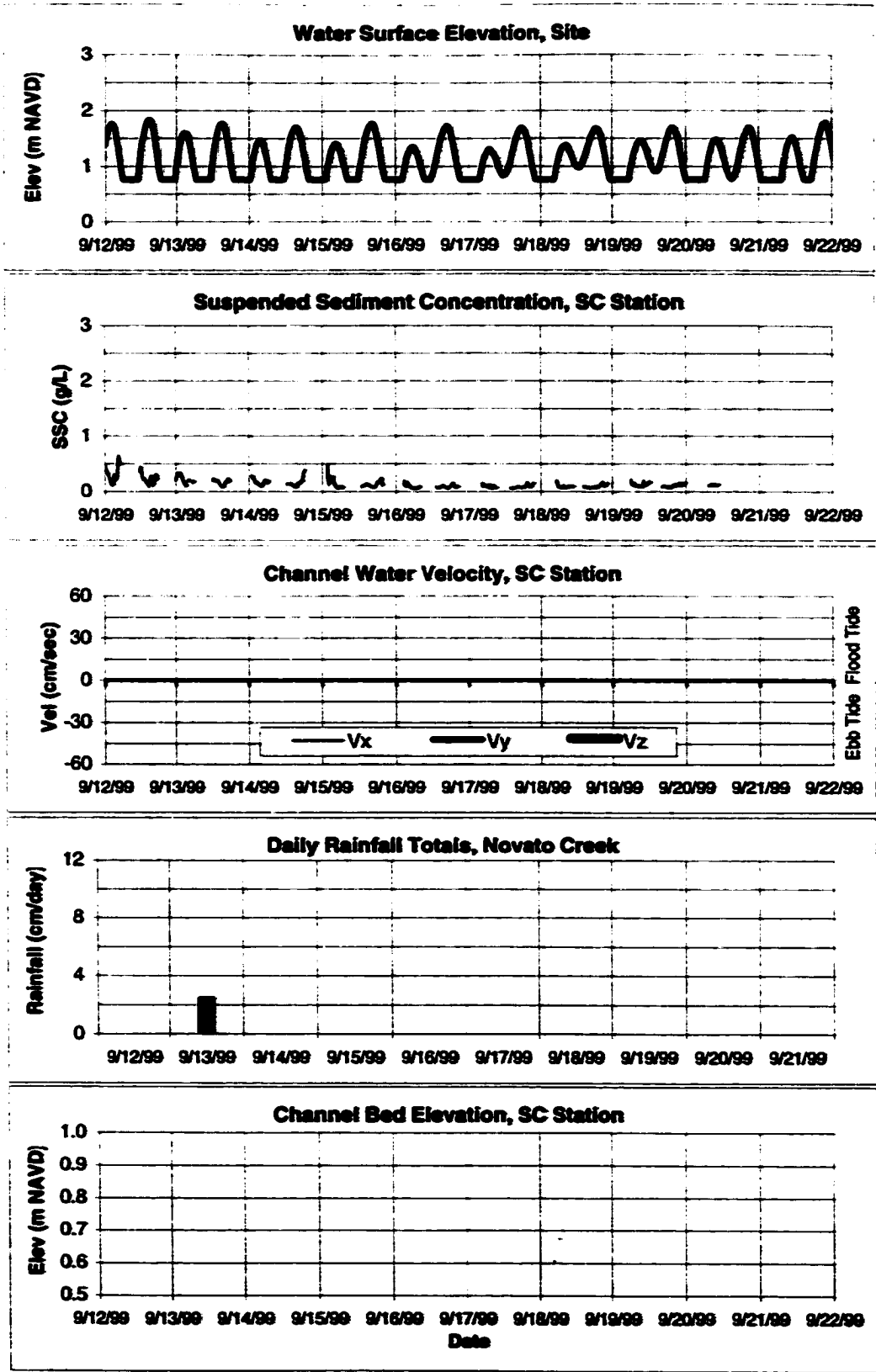
App B (5-23-02).xls: 58



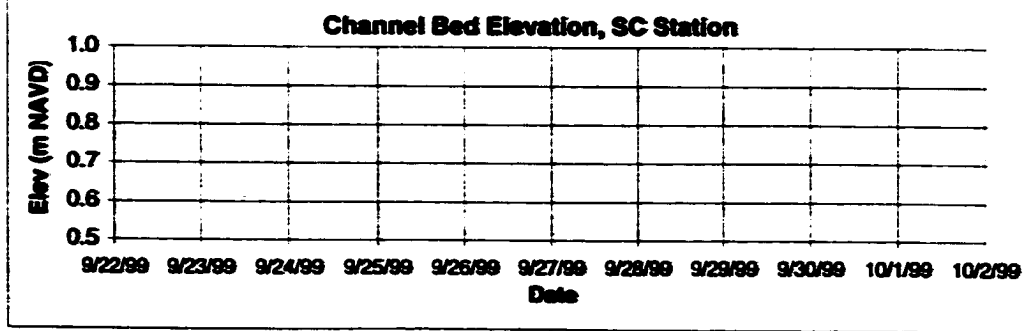
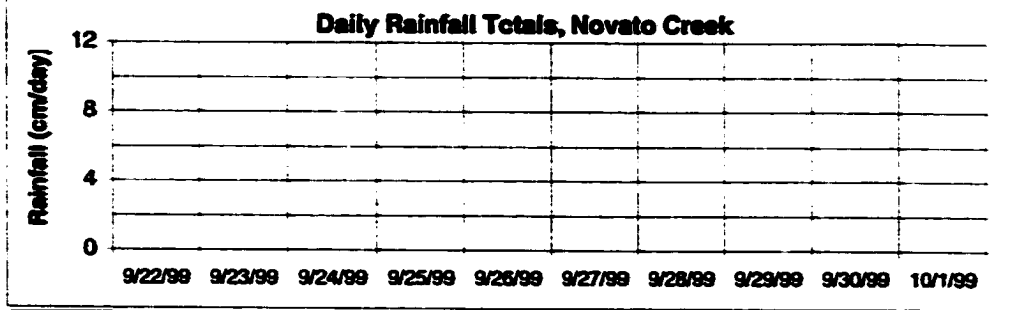
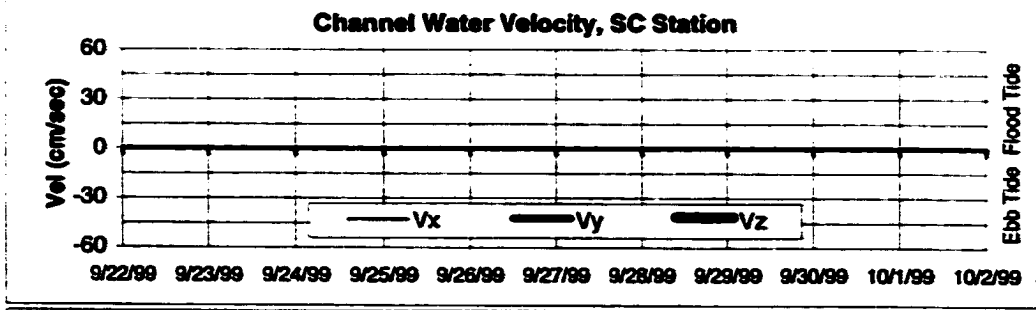
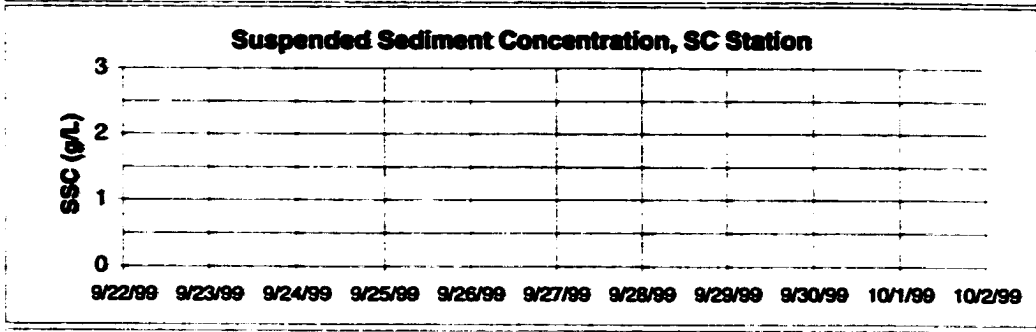
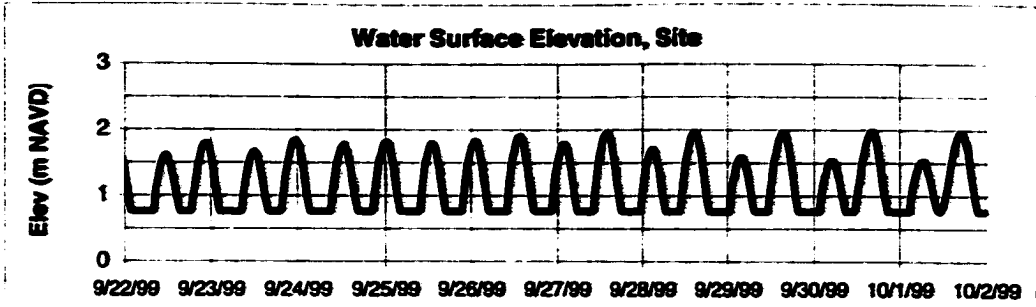
App 8 (5-23-02).xls: 59



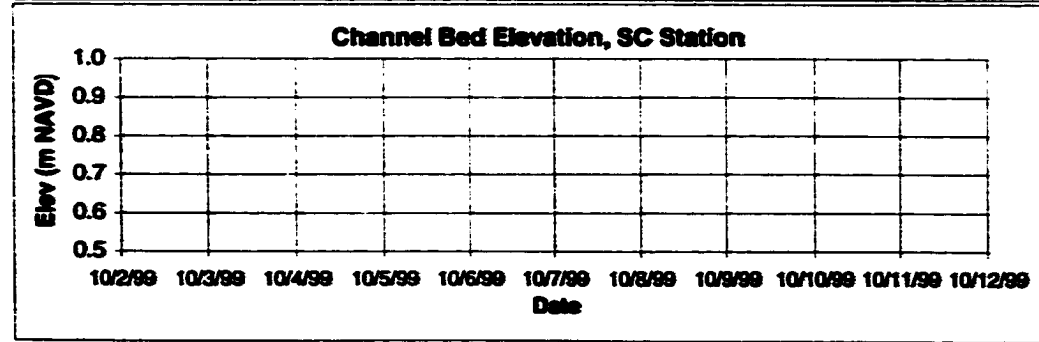
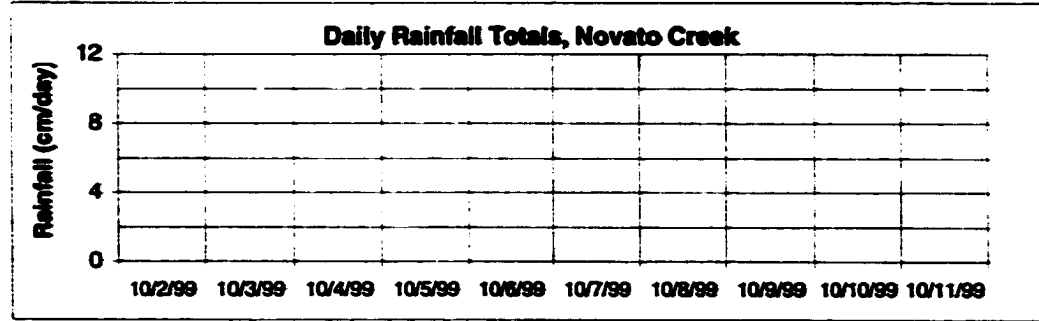
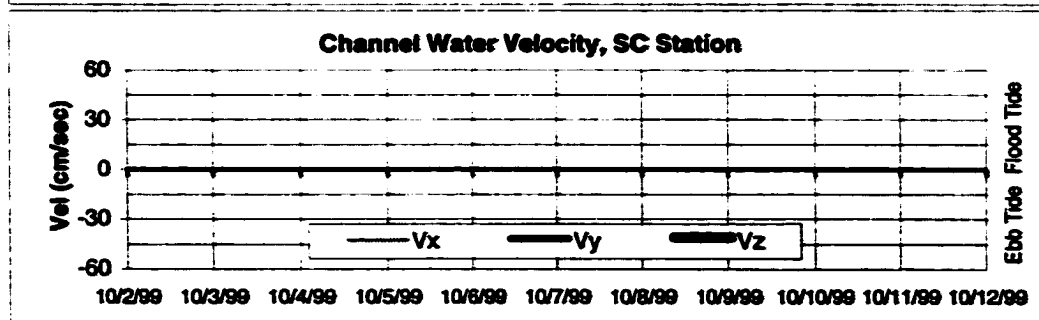
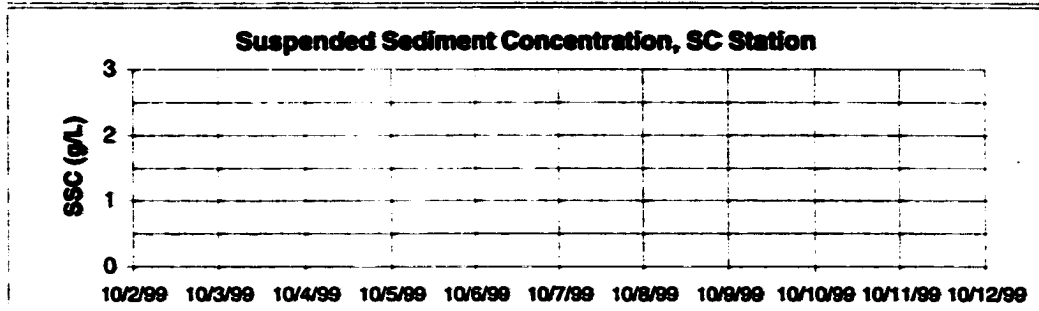
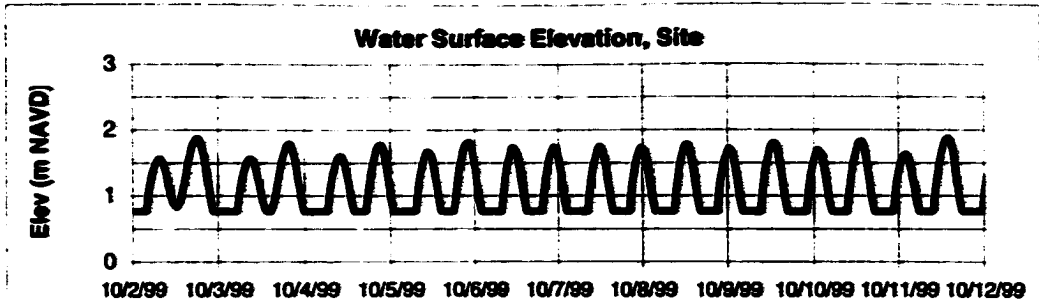
App B (5-23-02).xls: 60



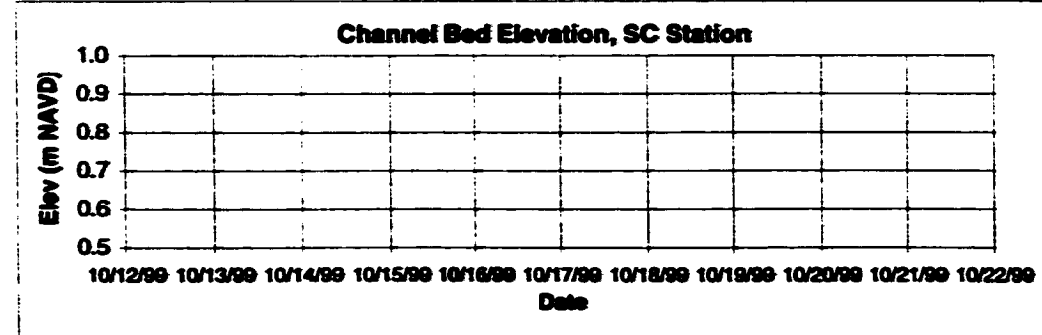
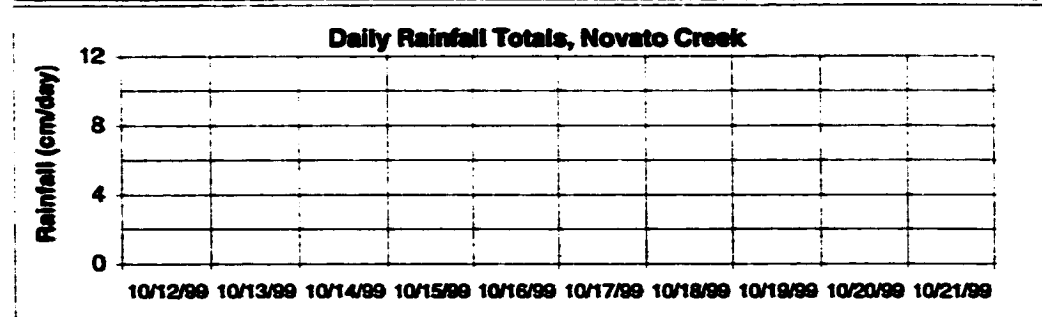
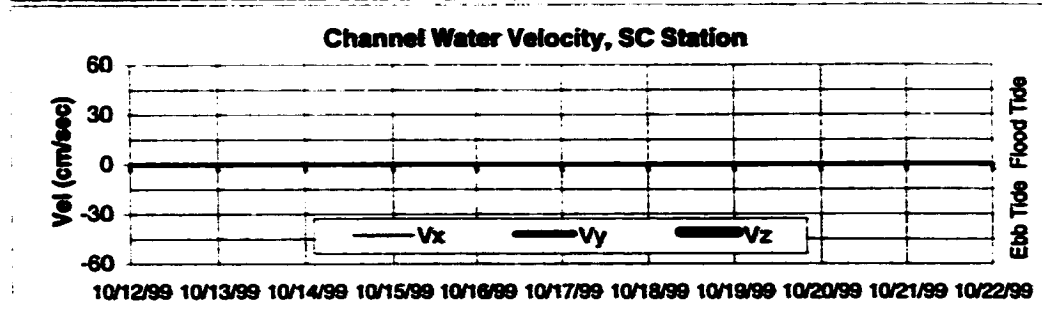
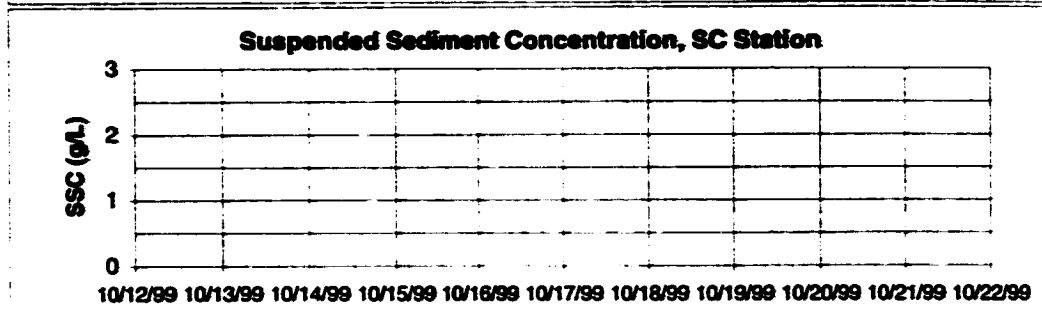
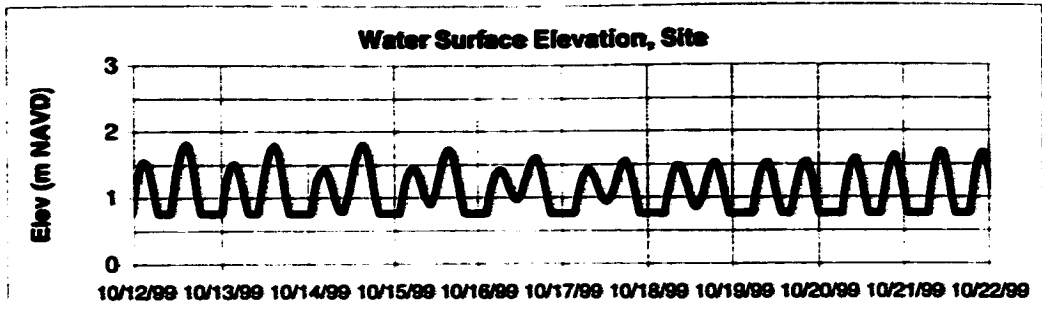
App B (5-23-02).xls: 61



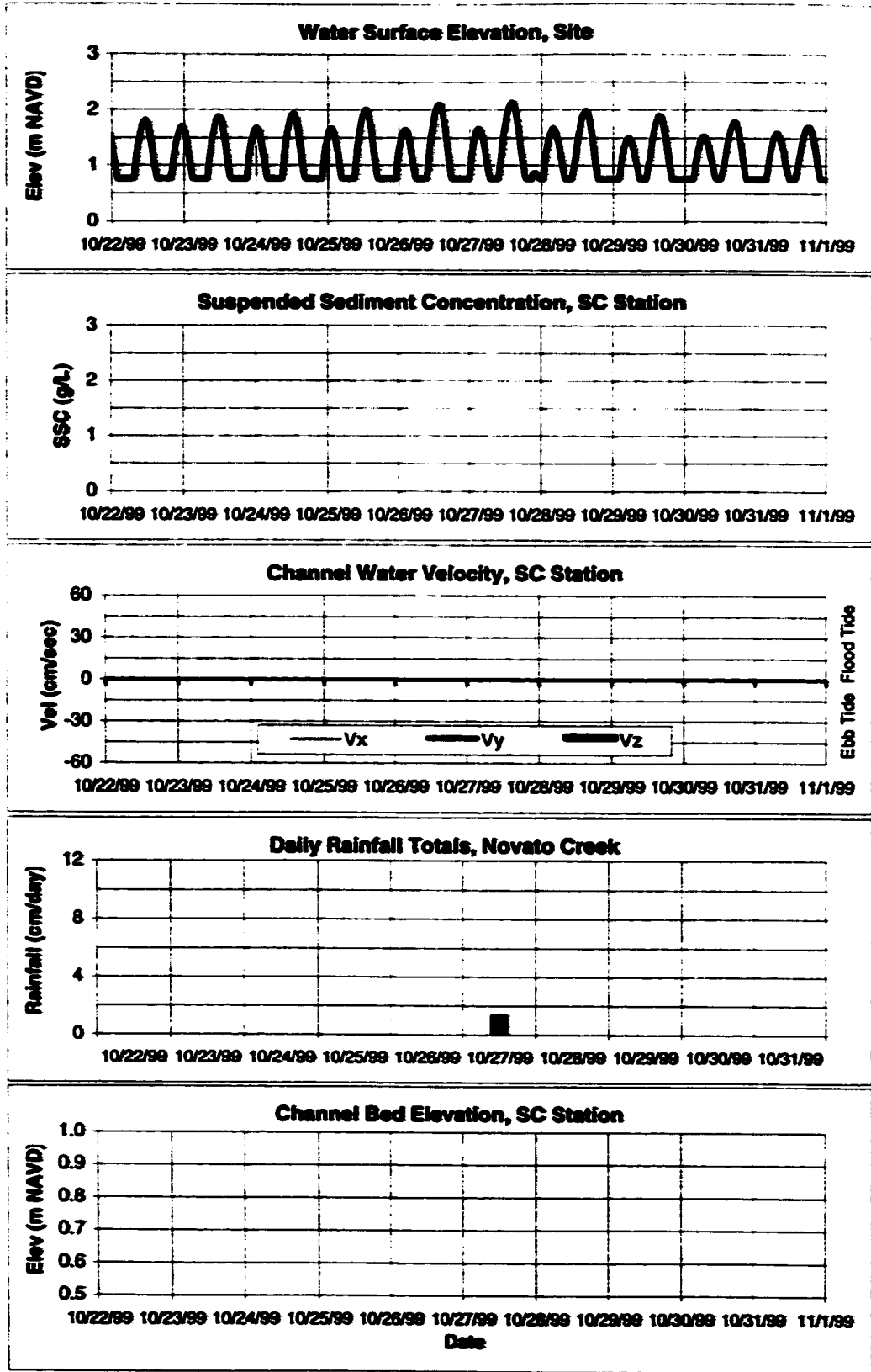
App B (5-23-02).atc: 62



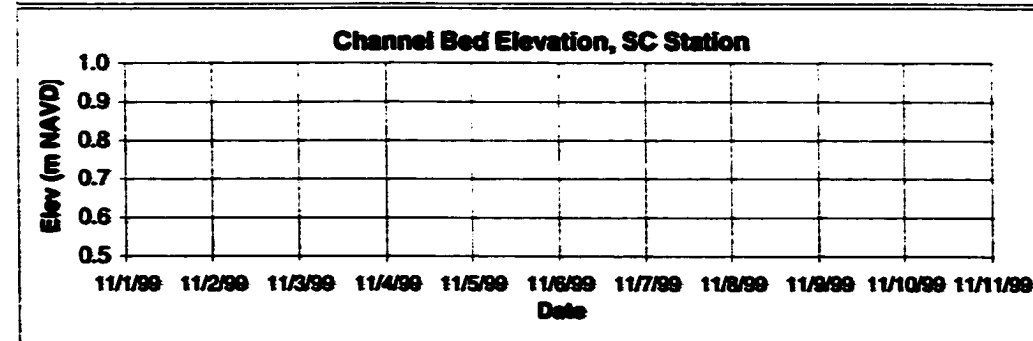
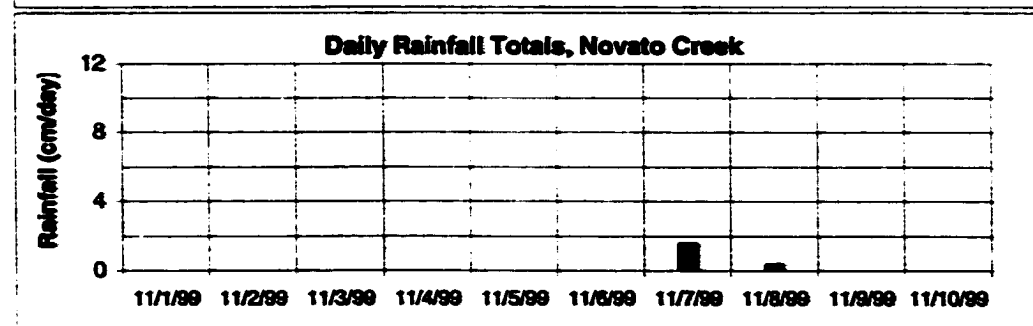
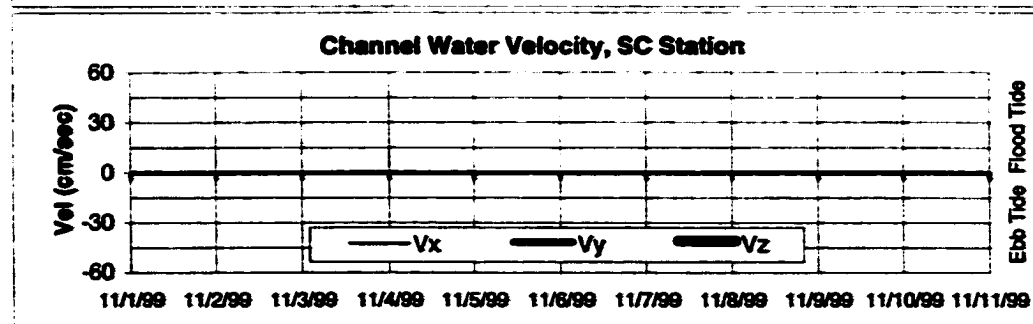
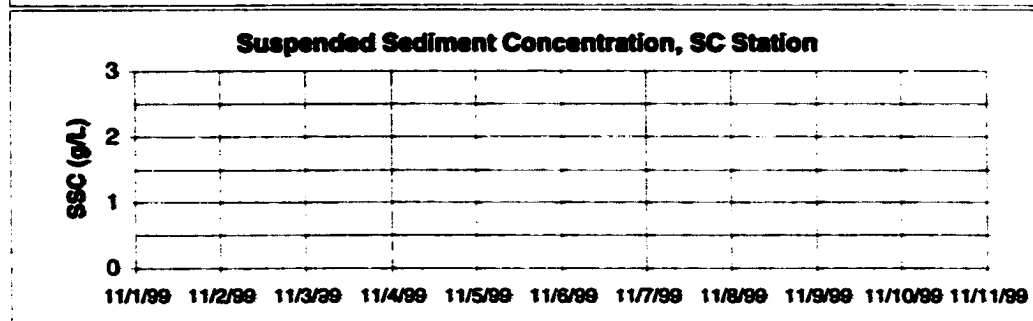
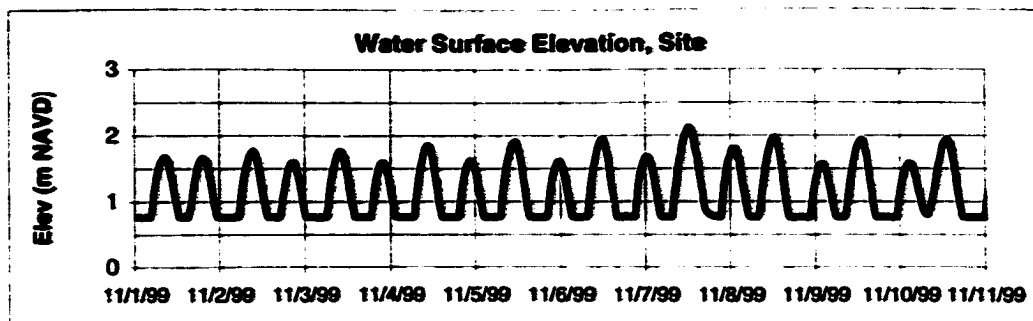
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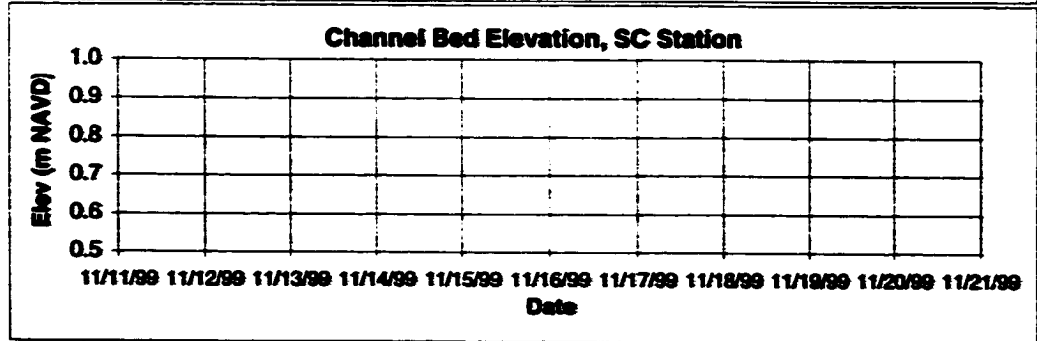
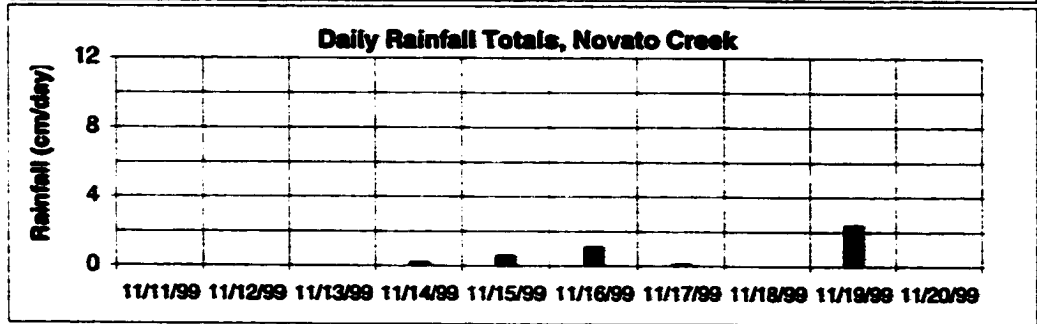
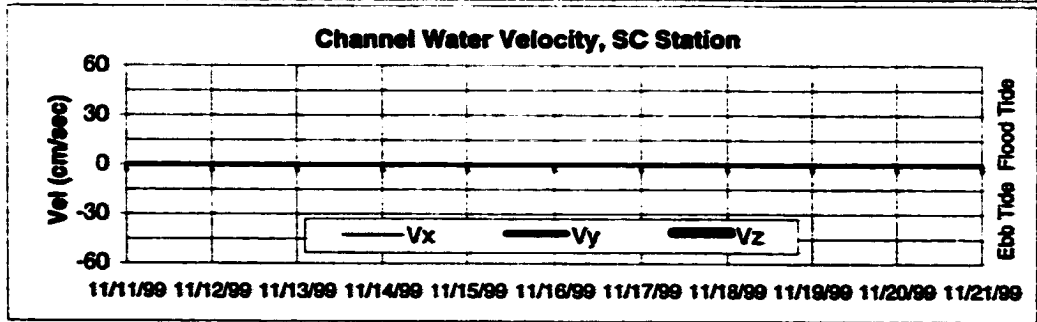
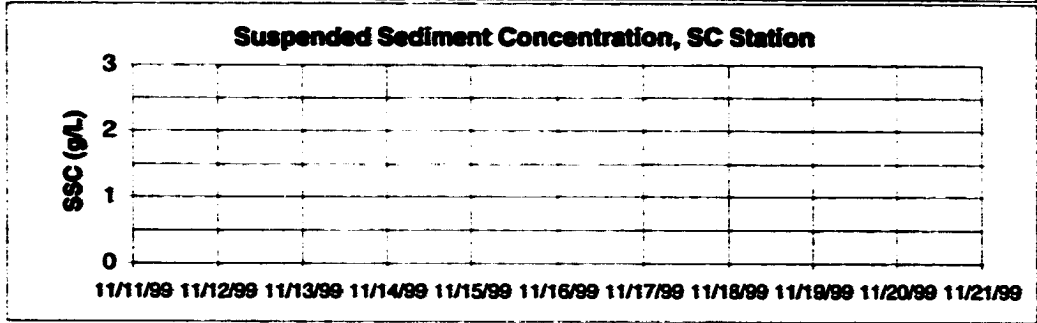
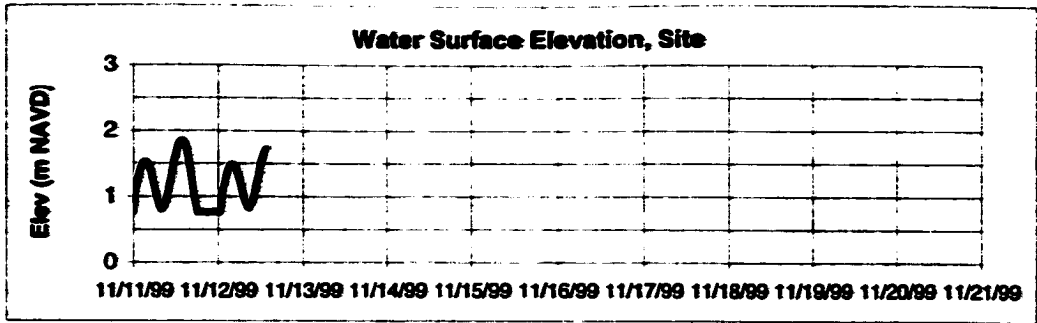
App B (5-23-02).xls: 64



App B (5-23-02).drc: 65



App 5 (5-23-02).xls: 65



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