Chapter One. INTRODUCTION

I. Rationale

Hydroperiod — the temporal pattern of overbank flooding and drying — has long been recognized as one of the major determinants of tidal marsh[1] structure and function. More generally, tidal regime – the temporal pattern of water level[2] in tidal estuaries, channels, and other coastal areas – controls many physical and biological processes in these areas. However, the theoretical development of these concepts in the scientific literature is imprecise and incomplete. Specifically, little has been written on the characterization of hydroperiod and other estuarine tidal regimes; on the determinants, spatial patterns, or evolution of these regimes; on the mechanisms through which hydroperiod types influence marsh groundwater, geomorphology, and ecology; or on the feasibility and efficacy of tidal hydroperiod manipulation as a resource management tool. These broad gaps provide the general motivation for this work.

The specific themes, scope, and methods of work presented in this dissertation, in turn, are motivated by seven interrelated concerns:

First, the spatio-temporal distributions of marsh landforms, soils, plants, and animals are substantially controlled by processes (including sediment deposition and resuspension, channel evolution, sub-surface chemical transformation and water flow, plant succession,

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[1]In general, "tide marsh", "tidal marsh", and "tidally-influenced marsh" will be used interchangeably throughout this thesis. Where a distinction matters, it will be made clear.

[2]"Water level", "water surface elevation", "sea surface height", and "stage" are other generally synonymous terms. Subtle distinctions will be discussed in detail in Chapters Two and Four.

animal activity, etc.) that are themselves heavily influenced by the frequency and intensity[3] of overbank flooding and drying[4]. Therefore, fully understanding marsh form and function will require essentially complete understanding of overbank flooding and drying.

Second, while overbank flooding and draining on tidal marshes is largely controlled by the water level in the nearest ocean[5], the temporal patterns of stage along ocean boundaries are often complex, subtle, and poorly described. Potentially significant patterns, both regular and irregular, occur in oceanic water level on a number of time scales, yet many of these patterns are not obvious in classic harmonic constants or tide prediction tables.

Third, these complex temporal patterns of sea surface height in the coastal oceans largely determine stage around and in near-by tide marshes if adequate time is allowed for wave propagation. However, intervening shallow basins, rivers, wind, built structures, and other local influences can all lead to differences in the time-corrected elevations of ocean and marsh waters. Specifically, because marsh formation is generally incompatible with exposure to oceanic storms, the open water immediately bordering a tidal marsh is usually an estuary (or other protected embayment). Therefore, water levels at the marsh margin and in marsh channels potentially differ from simultaneous water surface elevations in the nearby ocean not only because of lags inherent in the propagation of tidal-frequency waves, but also because of hydrodynamic processes within the estuary and the marsh channels, and also at ocean-estuary and estuary-marsh channel transitions. This means that better understanding and prediction of tidal marsh hydroperiod will generally require improvements in

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[3]The intensity of flooding includes both duration and water depth. The intensity of drying includes duration and severity of subsurface water tension.

[4]Citations are provided in Chapter Two for arguments presented in these first paragraphs.

[5]All water bodies large enough to generate tides will be termed “oceans” or “the sea” in this thesis.

understanding and prediction of estuarine water levels, incorporating harmonic interactions, non-tidal influences, in-estuary and channel hydrodynamics, and boundary transitions.

Fourth, while marsh hydroperiod strongly influences local topography, soils, and ecology, these variables also strongly influence hydroperiod. Specifically, the expression of estuarine or channel stage as overbank flooding and draining is largely determined by marsh plain elevation, by landforms (e.g. channels & runnels, levees, ponds), by soils[6] (e.g. infiltration, sub-surface flows), and by vegetation (e.g. resistence to surface flows, evapotranspiration). Accurate predictive models of tide marsh hydrology, geomorphology, pedology, or ecology will therefore require an understanding of the directions and strengths of causal relationships, and the structure of feedback mechanisms, between a wide range of physical and biotic variables.

Fifth, important records of environmental change in estuarine marshlands and in their watersheds are potentially preserved in tide marsh sediments, yet reliable paleo-environmental reconstruction based on sediment cores apparently requires a more robust understanding of the linkages between their topography, hydrology, ecology, and sediment deposition processes than has yet been published.

Sixth, tidally-influenced marshes, estuaries, and coastal zones in general have long been impacted by human activities, and the rate of their loss or deterioration due to diking, drainage, fill, pollution, water diversion, introduction of non-native species, etc. is high. On the other hand, there have been concerted efforts in recent decades to slow and reverse these trends through natural resource protection, enhancement, and restoration activities. Effective

[6]For this discussion, marsh soil, sediment, and substrate are considered synonymous. Detailed distinctions will be provided in the next chapter.

management and restoration of these environments will require both site-specific monitoring and regional change detection. These, in turn, will require robust tools for classification, measurement, and delineation of marsh landforms, ecosystems, and habitats.

Finally, tide marshes and estuaries are marginal places geographically, legally, and academically. Therefore, discussions of their status as places, as entities, as landscapes, or as ecosystems are often characterized by considerable ambiguity and taxonomic uncertainty.

Resolution of these interrelated challenges will require an integrated approach to estuarine and marsh systems, and in this thesis I will argue that tidal regime/hydroperiod is an appropriate organizing principle for these discussions. First, because the flooding and draining of tide marshes is ultimately due to oceanic tides which are distorted on their passage through estuaries and marshes, hydroperiods are end members of series of increasingly complex and irregular tidal regimes, starting with the open ocean. Second, hydroperiod can serve as an easily measured primary variable to test hypotheses of interacting mutual causality between other physical or biotic variables, emergent properties of estuarine and tide marsh systems (including habitat values or dynamic responses to perturbations), and/or evolution of tide marsh form and function. Third, hydroperiod characterization, which summarizes estuarine or marsh functioning, appears to be a useful management monitoring technique in estuaries and their marshlands. Finally, discussions of tidal regime/hydroperiod provide rich opportunities to explore methodological concerns — particularly classification and delineation — central to all scientific inquiry.

In summary, this thesis is a detailed exploration of tide marsh hydroperiods and other estuarine tidal regimes, using the San Francisco Estuary as its primary case study. While this thesis is not a comprehensive investigation of tide marsh or estuarine hydrodynamics, ecology, or geomorphology, it does provide theoretical tools to help explain and integrate these topics. The introductory chapters, therefore, explain the significance of hydroperiods and other tidal regimes both for tide marsh/estuary studies and more broadly.

II. General Approach and Organization

This thesis approaches tide marsh hydroperiod and other tidal regimes through one overall theoretical model. As noted before, water surface elevations on tidal marshes do not generally match the elevation of the nearby ocean with high fidelity. Instead, the flooding and draining of tide marshes is largely the end result of periodic oceanic water level fluctuations, which propagate as low-frequency waves through estuaries, along marsh channels, and over marsh plains; and which progressively diverge from oceanic patterns as they advance. This divergence can include lags/phase shifts, attenuation and sometime amplification of range[7], increase in mean water level, distortions in wave form associated with shallow water, elevation thresholds that function as selective filters, and a variety of non-tidal influences on stage. Thus, tide marsh hydroperiods are end members of sequences of increasingly complex and irregular tidal regimes starting with those in the open ocean.

This model is evaluated in this thesis using two major data sets. First, I collected and analyzed millions of pieces of field data on tidal stage and other relevant variables from fifteen field sites, primarily in the San Francisco Estuary of California, between 1992 and 2000. In particular, I designed and implemented tidal enhancement projects at the Peyton and Point Edith Marshes during this time, and data from these projects are presented in detail

[7]Resonance and reflection phenomena can increase tidal range in some basins. This will be discussed in detail in Chapter Two, Sections II and III.

as case studies. In addition, to better understand the water level conditions at the boundaries of marshes, I performed new statistical analyses on tide/stage data collected in the San Francisco Estuary by the U.S. National Ocean Service (NOS) and its predecessor agencies over the last 146 years. These analyses of archival data also illuminated a number of significant and previously undescribed patterns in water level variation in estuaries.

During this study, millions of specific pieces of data were collected, at many sites, over many years, for many specific purposes, using a wide array of techniques. Therefore, in the interest of clarity and emphasis I have modified the traditional scientific paper format of "Methods, Data, Results, Conclusions." Instead, this thesis is organized into thematic chapters, each including the study design and methods of data collection and analysis, the resulting data, and my interpretations and conclusions, for a specific set of questions. Because of the volume of data, I have selected only the most relevant and illustrative examples for direct inclusion in the text; future publications will present more of my observations.

To place all these data, analyses, and conclusions in their intellectual context, Chapter Two reviews the voluminous, diverse literature on tides and tide marshes and extracts the often implicit, sometimes contradictory, current "standard models" of estuarine and marsh tides. Although Chapter Two is not explicitly a historical review, historical materials are used to demonstrate the assumptions and implications of these intellectual constructs.

To place my data and conclusions in their geographic context, Chapter Three describes the San Francisco Estuary and its marshes, and my specific study sites both within and outside this estuary. While broadly theoretical work undertaken in this estuary is presented in the first chapter, more locally-focused or descriptive literature on its tides and marshes is included in Chapter Three.

I conclude my synthesis of existing observations and conclusions in Chapter Four, with the presentation of a systematic symbolic notation for the representation of water surface heights, other heights, and other related parameters. A formal concordance between my recommended symbols and terminology and those used by some widely-cited earlier authors is included as Table 17.

Chapters Five through Eight follow the sequential deviations in tidal stage and tidal regime that accompany the progression of tidal-frequency waves from the Pacific Ocean to mid-estuary marsh plains.

Specifically, Chapter Five covers my analyses of temporal variation in archival NOS stage data, primarily at the Golden Gate (the mouth of the San Francisco Estuary), including new interpretations of tidal regimes and tidal datums/means at that site and improved algorithms for forecasting water level at the Golden Gate.

In Chapter Six I present my analyses of spatial variation in stage in the Estuary, focusing on tidal wave form distortions associated with propagation of long waves in shallow open water and on fluvial and other non-harmonic contributions to open-water stage in estuaries. I emphasize contrasts between the Golden Gate and the mid-estuary Port Chicago NOS tide station, and I demonstrate and evaluate several new algorithms for estuarine stage forecasts at a variety of lead times.

A system for characterizing tidal wave forms and tidal regimes in tide marsh channels, based on analyses of my own data, is presented in Chapter Seven. This chapter includes detailed descriptions of my instrumentation and field methods and summary descriptions of supplemental numerical models. I demonstrate the significance of both natural and anthropogenic constraints on tidal exchange in marsh channel networks.

Chapter Eight presents my data and conclusions on the surface and subsurface hydrology of tide marsh plains. I examine overbank hydroperiod, the inefficiencies of flow that occur across marsh plains, and the impacts of in-channel and overbank processes on groundwater patterns. Quantitative measures of tidal propagation, dampening, and distortion are used to demonstrate a number of useful new concepts, including “channel efficiency”, “degree of tidal character”, and “effective elevation”. In particular, I present a rationale and several methods for the disaggregation of hydraulic variables such as flood frequency, depth, and duration that are generally associated with each other and with elevation in the literature. I also present new observations and theoretical models of subsurface processes, including complex pressure waves and drought feedback thresholds. This chapter concludes with new tide and marsh classification schemes based on multi-dimensional mappings of hydroperiod.

Finally, in Chapter Nine I summarize my observations and conclusions on estuarine and marsh hydraulics and I discuss the implications of the observed hydraulic processes and patterns for our understanding, management, and restoration of estuaries and their marshes. Specifically, I evaluate the significance of hydroperiod patterns for marsh ecology, geomorphology, soils, and the evolution of all of these. I conclude with an evaluation of the utility of specific hydroperiods as marsh management objectives and of the feasibility of using muted tidal regimes as tools for marsh management and restoration.

III. Reading this Thesis: A Note on Paradigms, Standard Models, Terminology, and Punctuation

I noted earlier that the primary purpose of these first chapters was to review the existing literature and to "extract" the "standard models" of estuarine and marsh tides. This statement merits further attention before I actually begin the review and extraction.

Progress in understanding the natural world requires clear communications between researchers and the growth of a body of scholarly literature; these in turn require the implicit or explicit agreement by a community of researchers on common epistemological and methodological principles — what Thomas Kuhn called "paradigms". Scientific paradigms include accepted definitions of key terms and "taken-for-granted" understandings of the nature of classification and nomenclature, causation and prediction, time and space, "good" data and evidence, and "standard models" of how the universe functions. It has been widely noted by historians and sociologists of science that these common understandings are reinforced by personal contacts, disciplinary divisions, narrowly-focused journals, and a range of other institutional practices in academia, government, and elsewhere (Kuhn 1996).

On the other hand, tide marshes and estuaries are marginal phenomena, both in the geographic sense (at the boundary between land and sea) and in the disciplinary sense (at the intersection of many academic fields of study). As such, they are the subject of a varied literature, with numerous obvious conflicts in terminology and theoretical structure. For example, beyond agreement on vascular vegetation and essentially tidal hydrology, there is a wide range in the extent to which tide marshes are seen primarily as distinctive hydraulic settings, as distinctive landforms or landscapes, as distinctive ecosystems, or as transitional zones or "fuzzy boundaries" between relatively discrete aquatic and terrestrial zones.

Similarly, estuaries are variously treated as distinct entities, as the lower reaches of rivers, or as arms of the sea. In addition, there are wide differences in the literature in the emphasis given to marshes and estuaries as things (e.g. The San Francisco Estuary) or as places (e.g. San Francisco Bay, San Pablo Bay, Suisun Bay, etc. – see Chapter Three). These distinctions, which substantially influence our understanding of these areas, will be elucidated and explored throughout this thesis.

This contrast between institutionalized paradigms and apparent disagreement on even the most basic terms can be reconciled by noting that numerous distinct disciplines and sub-disciplines have contributed to our understanding of tide marshes and estuaries, and that each has its own paradigms and standard models. Some of these disciplines are traditionally distinct sciences — hydrology, geomorphology, ecology, and physiology — while others are explicitly "inter-disciplinary" — oceanography, physical geography, estuarine science, and wetland science. While each discipline's paradigms allow for the articulation and testing of hypotheses, theories, and standard models, each also has the potential to constrain observation and interpretation. Therefore, the goal of my broad literature review is not only to present the published conceptual models of tides and tide marsh structure and function, but also to compare and contrast their assumptions (explicit or implied), and thus to begin the theoretical synthesis which I will extend in the following chapters.

One tool I will use is careful and explicit definitions of all potentially ambiguous terms[8], and then strict adherence to my recommended terminology. In general, definitions of terms will be presented in the general text at the first instance of potential confusion. For symbolic notation, I present a formal concordance with other authors as Table 17. In

[8]So please read the footnotes!

addition, three terms are so important and so ambiguous that I must address them briefly now – all three will be additionally and exhaustively discussed later in the text. "Tides" have been formally defined as the periodic rise and fall of the water resulting from gravitational interactions between Sun, Moon, and Earth (Hicks 1989). "Marshes" have been conventionally defined as areas of dense emergent herbaceous vegetation, where the soil is water-saturated with sufficient frequency and duration to exclude all plants except for a specialized flora adapted to very wet conditions (Mitsch and Gosselink 1993). A "flood" can be either the rising and overflowing of a body of water onto normally dry land, a rising tide, or the incoming current associated with a rising tide (Merriam-Webster 1997). Therefore, where there is any chance of ambiguity, I will use "rising tides" for flood tides, "incoming currents" for flood currents, and "overflowing" for water movement from in-channel to over-bank. I will generally reserve "flood" and "flooding" for the presence of detectible water on the over-bank surfaces of tidally-influenced marshes.

Finally, disciplinary and editorial norms are applied to matters of punctuation as well as to paradigm and word choice, and I owe the reader an explanation here for a practice that I will follow throughout this thesis despite the reservations of some grammarians. I am well aware that standard punctuation practice in the U. S. dictates that commas should be enclosed inside quotation marks (Goldstein 1998, p. 271), but in the interest of clarity I have chosen to follow the recommendations of the Chicago Manual of Style (1993, p161):

> "The British style of positioning periods and commas in relations to the closing quotation mark is based on the same logic that in the American system governs the placement of question marks and exclamation points: if they belong to the quoted material, they are placed within the closing quotation mark; if they belong to the including sentence as a whole, they are placed after the quotation mark. There may be some risk [of miscommunication with poorly placed commas and quotation marks] in such

specialized material as textual criticism, but in that case authors and editors may take care to avoid the danger by alternative phrasing or by employing, in this exacting field, the exacting British system. In linguistic or philosophical works, specialized terms are regularly punctuated the British way, along with the use of single quotation marks...."

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