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**DESIGN GUIDELINES
FOR TIDAL CHANNELS IN
COASTAL WETLANDS**

Prepared for

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Although this document remains a useful reference, parts of the document have been updated in a more recent study. In the more recent study, PWA has used additional channel geometry data to revise the channel geometry plots (e.g., channel depth v. tidal prism, top width v. tidal prism, etc.). PWA has also completed an additional study of the rates and patterns of channel evolution in restored sites. Parts of this document are updated in:

Williams, P.B., M.K. Orr, and N.J. Garrity. 2002. Hydraulic geometry: a geomorphic design tool for tidal marsh channel evolution in wetland restoration projects. Restoration Ecology 10:577-590.

Williams et al. (2002) contains revised hydraulic geometry relationships and data on the rates of channel evolution in restored sites. This paper is available on the PWA web site, www.pwa-ltd.com.

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1. INTRODUCTION AND STUDY APPROACH

Coastal wetlands lie at the interface between the land and estuarine or marine environment. For many years, coastal wetlands were thought to be suitable only for diking, draining or filling; they were often considered to be virtually worthless sources of mosquitoes and disease. In recent years, however, the essential hydrologic and ecological functions of wetlands have become increasingly appreciated, both by the lay public and by professional land managers. Protection of wetlands is now firmly institutionalized in the Section 404 regulations of the Clean Water Act and mandated programs of the Army Corps of Engineers, the U.S. Environmental Protection Agency, the U.S. Fish and Wildlife Service, and numerous state agencies.

In some cases, wetland creation is driven by the needs of developers or transportation agencies to find sites for mitigating the impacts of fill; in other cases, wetlands have been created or restored concomitantly with disposal of dredged material. A recent study by the National Research Council (1992) called for the restoration of 10 million acres of wetlands in the U.S. by the year 2010. As appreciation of wetland values has grown, attention has turned to the design methodology and technology available for creating wetlands (National Research Council, 1994).

The design philosophy of wetland creation differs fundamentally from the philosophy of traditional engineering practice. The traditional engineering approach aims at control of the forces of nature; a project is designed and built to certain specifications. Post-construction change and evolution of the project features is neither contemplated nor desired. In designing wetlands, however, the engineer tries to work with the forces of nature, creating a project that will continue to evolve as a wetland along certain predictable pathways. The natural processes of erosion, sediment deposition, channel migration, plant succession, etc. can all be accounted for in the project design, and used to create a wetland that will meet desired objectives.

The channel network is a fundamental part of any coastal wetland system. In designing a tidal wetland, the channel network must be designed to carry sufficient volumes of tidal water to meet project goals of water quality, tidal circulation and habitat. The purpose of this document is to set forth design guidelines, criteria and methods for designing channels in a created tidal wetland.

This report is organized in several sections. The first section discusses the patterns and processes involved in the development of tidal marshes, on the assumption that an understanding of the basic processes provides a basis for channel design. The next section discusses the ecological values, goals and criteria involved in channel design, since many projects are driven by biological goals. A brief section describes the engineering goals in channel design; it is assumed that the readers of this document will be generally familiar with this subject, and so this section is relatively short. Next, some empirical geomorphic relationships are discussed, and their application in channel design is illustrated. The shape

of channel cross sections is described from both empirical data and geotechnical considerations. The plan view (channel density and sinuosity) is also described empirically. The role of organisms in channel formation is discussed briefly, and the constraints on using natural tidal energy to create small channels is analyzed. Supporting material is organized into three separate appendices.

In a natural tidal system, the channel planform, cross section and slope are determined over the long run by the interaction of physical and biotic variables including tidal range, sediment size, vegetation, bioturbation, and geomorphic history. There is a substantial body of work that has attempted to quantify the relationships between channel morphology and independent physical and biotic variables, and hydraulic models are available that can calculate tidal flow in natural marshes. The state of the science is not advanced to a point, however, at which tidal slough channel dimensions can be derived solely from first principles. Instead, channel design has to rely heavily on empirical geomorphic relationships. The approach taken in this study is to develop a number of empirical relationships between, for example, channel characteristics and tidal prism, and to describe the theoretical basis for using these relationships.

At the outset it was hoped that empirical relationships could be developed that could be applied in different regions, for example in the Gulf Coast region, in eastern marshes and west coast marshes. Although data are available for tidal marshes in different regions, the assumptions and methodologies used in collecting different data sets are not uniform. This makes the comparison and design application of different data sets difficult. The geomorphic principals that govern the formation of tidal channels, however, do not vary from one region to another. By collecting some local data, engineers can extend the relationships, best quantified in this report for coastal California, to specific sites in other regions. Since sediment characteristics, land use history, vegetation and tidal range may vary within a region as well as between regions, it is always desirable to collect local data as a basis for design.

2. PATTERN AND PROCESS IN DEVELOPMENT OF TIDAL MARSHES

In developing a methodology and guidelines for designing channels in tidal wetlands, it is important to keep in mind the diversity and variability of estuarine wetlands in the U.S. Estuaries and tidal influence differ greatly along the US coasts, with the highest tidal ranges along the Pacific and North Atlantic coasts and the lowest along the Gulf of Mexico (Table 2-1). There are a few large estuaries (e.g., the Chesapeake, San Francisco Bay) and many tiny ones. Some systems are marsh dominated; others are mostly open water. From the perspective of the biota, it is likely that the relative importance of marsh, channel and open-water components differs among regions. The small marsh-dominated systems of the northeast and southwest may have more in common than either group has with large open-water-dominated estuaries of their respective coastlines, such as the Chesapeake and San Francisco Bay. Size of system and relative area of habitat type (marsh, channel, open water) are only two of the landscape-level differences that are important to biota. Tidal and freshwater inflow regimes dictate salinity patterns, and the strength and direction of currents influence seed dispersal, larval distributions, and animal movements. A striking difference is the low tidal range in protected Gulf estuaries compared to that of open-coast systems on the Pacific. A tidal channel that fluctuates 2-3 m per day will have distinctly different environmental conditions, and hence species composition, from one that varies little from day-to-day, even if its seasonal range (e.g., storm-generated high water) is great.

On a more local scale, there is wide variation in tidal channel size, density, and sinuosity among coastal wetlands. Pethick's (1992) study of the geomorphology of some North Norfolk and Essex saltmarshes found that tidal creeks form to dissipate tidal energy and that tidal energy has a significant impact on the morphology of channels in open coastal wetlands, even though storm-generated energy is much stronger. Tidal creek size and morphology also depend on the tidal prism (Pethick, 1992).

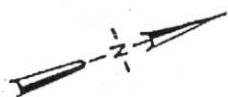
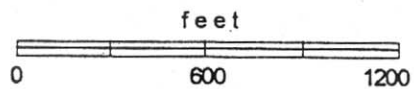
There is an interaction between tidal creeks and the biota, with vegetation tending to stabilize and burrowing animals tending to destabilize tidal creek banks. Virtually no studies have been able to quantify the relative importance of physical vs. biological influences on tidal creek geomorphology. Nor is it clear how the total physical configuration of tidal creek networks influences their use by any group of organisms. Work of this type has been confined to microhabitat preferences, rather than whole-network evaluations. A larger-scale view is needed before definitive recommendations can be made on how to configure constructed marsh channels and creeks.

A tidal marsh consists of at least three main interrelated geomorphic features: a gently-sloping mudflat, a channel network and a marsh plain. In some marshes, tidal ponds or pans occur within the marsh plain. The form of these features is a response to 1) the input of suspended sediment in tidal water; 2) the physical effects of dominant vegetation; 3) the input of wave and tidal energy; and 4) relative rise of sea level. Saltmarshes are the physical expression of the equilibrium between stress (wave and tidal) and strength (of cohesive sediments and vegetation). According to geomorphic theory, the marsh develops in

TABLE 2-1

CHARACTERISTICS OF U.S. ESTUARIES
(Mostly from McIvor and Rozas in Review;
Pacific Coast Summary from Personal Experience of J. Zedler)

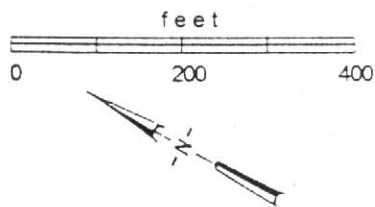
<i>North Atlantic Estuaries</i>	=	12.7 percent of coast
	C	estuaries are relatively small;
	C	tidal ranges large (>2m)
	C	high marsh (<i>Spartina patens</i>) dominates
<i>South Atlantic Estuaries</i>	=	18.3 percent of coast
	C	coastal plain estuaries formed from drowned river valleys
	C	extensive intertidal areas
	C	large areas of low marsh (<i>Spartina alterniflora</i>)
	C	semidiurnal tides
	C	1-2 m range in mid Atlantic (Cape Cod to northern NC)
	C	2-3 m range at middle of Georgia (Sapelo Island)
	C	< 1 m range north and south Georgia
<i>Gulf of Mexico Estuaries</i>	=	60.1 percent of coast
	C	mixed semidiurnal tides from Suwannee R. to Apalachicola Bay, FL, and from Atchafalaya Bay to Sabine Lake
	C	diurnal tides from St. Andrews Bay, FL to the Miss. Delta
	C	tidal range small (e.g., 30 cm)
	C	regularly and irregularly flooded marshes
	C	regularly flooded marshes dominated by <i>Spartina alterniflora</i>
	C	irregularly flooded marshes dominated by <i>Juncus roemarianus</i>
<i>Pacific Estuaries</i>	=	7.1 percent of coast
	C	semidiurnal mixed tides
	C	3 m range in southern California, 1.1 m average amplitude
	C	marshes concentrated in a few bays (e.g., San Francisco Bay)
	C	pickleweed (<i>Salicornia virginia</i>) dominant in marshes with and without tides;
	C	<i>Spartina foliosa</i> present in lowest elevations of fully tidal marshes



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The China Camp Marsh,
Marin County, San Francisco Bay

Figure
2-1



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The Audubon Marsh at Newark,
Alameda County, San Francisco Bay

Figure
2 -2

the long run in a way that resists long-term morphological change, and distributes the dissipation of tidal and wave energy over space.

The development of tidal channels in a marsh is a response to the input of tidal energy rather than storm wave energy. In one sense, the channels in tidal marshes represent an interesting contrast with upland stream channels. In the latter, discharge (Q) is independent of the channel geometry, whereas in a tidal channel, the discharge at a given cross section is determined by the way in which flow has shaped the channel between the cross section and the tidal boundary. As a result of this interdependence, tidal channels are thought to change more rapidly in width and less rapidly in depth in a downstream direction than do upland channels (Myrick and Leopold, 1963).

The channel system may be thought of as a device for dissipating tidal energy. Langbein (1963) showed that the concept of entropy in landscape evolution can be applied to tidal channels. This implies that the work done per unit area of channel boundary by tidal forces (or tidal power) should tend to be equal throughout the channel system, and the channel network should adjust in such a way as to minimize the total work for the entire channel. Pethick (1992b) found that for the Humber Estuary in England (a large estuary rather than a slough channel), the constant power hypothesis held over some reaches, but not for the estuary as a whole, perhaps due to its geomorphic history.

In a mature tidal marsh, the channel planform is often sinuous, resembling a meandering upland stream channel. Pstrong (1965), who has described the evolution of channels in tidal marshes, notes that the initial evolution of tidal channels appears to occur not in a vegetated marsh, however, but on the unvegetated mudflat. A newly-dissected mudflat is drained by a few widely-spaced and roughly parallel first and second order channels. These channels may shift and migrate due to deflection of the direction of the ebb-tide current or normal meandering. Once vegetation has invaded the mudflat, the channels become more stable; lateral migration proceeds by undercutting and bank caving. The heads of channels may erode into the growing marsh plain due to the increased hydraulic gradient between the vegetated marsh and the mudflat. The channels may thus be thought of as remnants of the mudflat around which the vegetated marsh plain has grown, or as "superposed meanders." Once the vegetated marsh plain has developed, the channels may incise, thus concentrating flow across the mudflat.

Figure 2-1 shows a mature marsh on the shoreline of San Francisco Bay. Vegetation has recently invaded the mudflat, and the shoreline has shifted bayward. Note that channels that have formed recently on the sloping mudflat are less sinuous than the channels in the older marsh; this may reflect the higher slope on which the channels formed. Figure 2-2 is a mature marsh from south San Francisco Bay; note the well-developed pan in the center of the photograph and the complex drainage network that has formed.

In a mature marsh, vegetation plays a dominant role in processes of channel change. A dense root mat in the upper foot or so of marsh soil greatly increases the cohesiveness and strength of the soil; in west coast tidal marshes, *Salicornia* is greatly more effective than *Spartina* in contributing the strength of the marsh soil (Pstrong, 1969). Collins *et al.* (1987), in a study at Petaluma Marsh in San Francisco Bay, found

that *Salicornia* may actually bridge across narrow tidal channels, providing a base for sediment deposition and converting open channels to subterranean pipes. The occlusion of small first order channels was thought to be compensated for by headward erosion of other small channels into the mature marsh plain. That study also found that plant debris may make a significant contribution to the accumulation of marsh sediments. At 50 meters from the nearest channel, organic matter constituted up to 45 percent by weight of the marsh sediments in the upper 45 cm; at channel banks, it accounted for only about 10 percent by weight.

Although tidal energy plays an important role in forming channels, storm-generated waves may play a dominant role in the location of the margin between mudflat and vegetated marsh. Pethick (1992a) showed how in the open-coast marshes at Essex, England, the mudflat-marsh plain profile responded to variations in wave energy in a manner consistent with classic beach theory. During major storms, the marsh edge is eroded, and sediment is deposited on the mudflat, with a resulting flattening of the profile. This allows the wave energy to be dissipated over a greater distance. During prevailing conditions, the mudflat is eroded, and sediment is deposited on the marsh plain. In smaller, more open systems (such as San Francisco Bay marshes), this relationship between mudflat and marsh plain might not hold, since eroded sediment can be transported by tidal currents into or out of the marsh/mudflat system.

Tidal marshes are dynamic rather than static systems. The development of the marsh plain and the channel system occurs in response to rising sea level, changes in inputs of tidal energy, and the concentration of sediment in tidal waters. As sea level rises, or the marsh subsides, the duration and depth of flooding increases, and the opportunity for sediment deposition increases, even though the greater energy in over-marsh flow may prevent deposition. Sea level rise may also increase water depth and wave energy on the mudflat, thus increasing the erosion of the marsh margin and increasing the concentration of sediment (Pethick, 1992a). If the concentration of sediment in tidal water is decreased, however, the vertical accretion of the marsh plain may be reduced. The elevation of the marsh plain may thus increase over time in response to sea level rise or increases in sediment concentration. Given an adequate sediment supply, the marsh plain elevation at a given time represents an approach toward a steady-state elevation, even though the ultimate steady-state, with a static, fixed elevation, may never be reached. As sea level rise accelerates over the next century, the extent to which marsh accretion can keep pace is an open question (Reed, 1988).

An interesting and open question in tidal marsh geomorphology is whether the channel network is formed and dominated by the flood tide or the ebb tide. In one view, a tidal marsh is primarily a device for dissipating flood tidal energy; flow velocities during the flood tide are attenuated toward the head of the system, so that the lower reaches experience effective channel-forming flows in both directions. The marsh plain is thought of as dead space between the channels that does not play an important geomorphic role. In the second view, ebb flows are dominant throughout the channel system; the channel network and the marsh plain that drains into it may be thought of as a drainage basin, analogous to an upland drainage basin. Most likely, neither view by itself is entirely satisfactory (French and Stoddart, 1992).

3. ECOLOGICAL VALUES, GOALS AND CRITERIA

The channels in a tidal marsh are not just conveyance facilities for water. They also provide important habitat for the plants and animals of the marsh. In designing the channels, the biological goals for the created or restored wetland must be considered. This section will discuss the biological value of channels as habitat, and how these values can be taken into account in developing goals for channel design.

3.1 BIOLOGICAL VALUES

Coastal wetlands are highly valued for their high primary productivity and related biological functions. Along the Atlantic and Gulf of Mexico coasts, and in the Pacific Northwest, the greatest value that is widely recognized is the fisheries support function. The paradigm is that intertidal marshes produce high quantities of vascular plants which decompose into small particles (detritus) that is consumed in-situ or transported to coastal waters (outwelling) where it supports a food chain leading to fishes. In southern California, the esthetic aspects of biological diversity take precedence for a large urban population that values bird watching, nature interpretation, and open space. Emphasis on biodiversity is further related to major losses in habitat area (e.g., 85% saltmarsh loss), with a long list of sensitive and endangered species and much of the fish-support function (e.g., California halibut) no longer present.

The creation of tidal marshes both planned and inadvertent from dredged material has led to considerable research on the ecological values and development rate of new tidal marshes. Monitoring studies have shown that tidal marshes can be created successfully from dredged material, the ecological values often differ from natural mature tidal marshes, and some years may be required for a newly-created marsh to reach the productivity of a natural mature tidal marsh (Landin *et al.*, 1989)

3.2 IMPORTANCE FOR FISHES

Marsh surfaces are used by fishes in the Atlantic and Gulf Coast estuaries, especially by juveniles for refuge and foraging. Channels leading to the marsh are important for fish production. Rozas (cited in McIvor and Rozas, in review) reported 51 fish species in 24 families and 7 crustacean species in 3 families using saltmarshes of the southeastern US. McIvor and Rozas (in review) conclude that marsh habitats are important to fishes and crustaceans even though these habitats are accessible only one to two hours a day.

Studies of marsh use by Pacific Coast fishes and invertebrates are rare. The limited attempts to collect fishes at high tide in the southern California marshes have failed to verify substantial fish use at either Tijuana Estuary or an intertidal marsh and mudflat habitat that was constructed on dredged material in

South San Diego Bay. Nine flumes were placed and sampled in these two sites, and only a few fishes were caught.

The Pacific Northwest estuaries provide critical habitat for a variety of fishes, especially salmon. Simenstad *et al.* (1990) lists different assemblages for mudflat, sandflat, gravel-cobble, eelgrass, and nearshore subtidal soft bottom, nearshore subtidal hard substrate, and water column habitats.

3.3 BIODIVERSITY

Along the California coast, more emphasis has historically been placed on esthetic values and biodiversity support (Table 3.3-1) than on fish production of tidal channels. In this region, wetland losses have been especially high, and many species are in danger of extinction. However, channel habitats are often proposed to be constructed to mitigate damages to fish habitat elsewhere. Generally, a few large, deep channels are constructed, with no attempt to mimic the complex dendritic systems that occur in natural marshes.

3.4 RELATIONSHIPS BETWEEN BIOTA AND CHANNEL FEATURES

3.4.1 Substrate Type and Associated Features

Exactly how tidal channels enhance the biodiversity and functioning of coastal wetlands is not clear. However, McIvor and Odum (1988) have suggested that the geomorphology of tidal creeks may partially determine differences in wetland habitats. Obviously, channels provide a route for tidal waters to flow and ebb, but they also provide habitat for a wide range of organisms, both directly and indirectly (Table 3.3-1). Vascular plants and/or seaweeds occur in areas with suitable substrate and light availability. Fishes live in the water column and burrowing species live in the benthos, often co-habiting with benthic invertebrates. Burrowing invertebrates live in the channel sides and bottoms. Birds forage along the edges, probing the sediments or spearing fish from shallow water. Dabbling ducks also feed in the shallow waters, while diving ducks use deeper waters. In addition to these conspicuous organisms, there is a whole host of smaller attached and free-floating organisms, including phytoplankton, zooplankton, epibenthic algae, epifauna and infauna.

For most of the "attached" (epifaunal) and burrowing (infaunal) organisms, substrate particle size is the most important environmental variable. Some species of plants and animals have large attachment organs (holdfasts or ft) and will glue themselves to large pebbles or rocks (e.g., many seaweeds, mussels, and barnacles). Other plants, such as eelgrasses, have roots that penetrate the substrate, while various animals dig into the sediments. Depending on the structure of their burrowing appendages, these animals will be successful only within a relatively narrow range of particle sizes. The ghost shrimp, *Callinassa*

TABLE 3.3-1

**COMMON "BIODIVERSITY-SUPPORT" OBJECTIVES FOR COASTAL WETLAND
RESTORATION PROJECTS IN SOUTHERN CALIFORNIA**

Habitat type	Sensitive species
Tidal cordgrass marsh	Light-footed clapper rail (<i>Rallus longirostris levipes</i>)
Pickleweed marsh	Belding's Savannah sparrow (<i>Ammodramus sandwichensis beldingi</i>)
High intertidal marsh	Saltmarsh bird's beak (<i>Cordylanthus maritimus</i> ssp. <i>maritimus</i>) Wandering skipper (Lepidoptera: <i>Panoquina errans</i>)
Salt panne	Tiger beetle (Coleoptera: <i>Cicindela</i> spp.)
Mudflats	Shorebird community
Riparian willows	Least Bell's vireo (<i>Vireo bellii pusillus</i>)
Bird nesting islands	California least tern (<i>Sterna antillarum browni</i>), Western snowy plover (<i>Charadrius alexandrinus nivosus</i>)

californiensis, is typically found burrowing in sand, while the bent nose clam, *Macoma nasuta*, can live in soft mud, along with many polychaete worms.

Substrate type is further critical to marsh vegetation development. At San Diego Bay mitigation sites, coarse sandy substrate fails to trap and hold nutrients and organic matter, with the result that nitrogen supplies are limiting to plant growth (Langis *et al.* 1991, Gibson *et al.* in press). Because nitrogen supplies are inadequate, vegetation canopies are too short to support nesting of the light-footed clapper rail; hence, it is likely that the failure of rails to use the mitigation marsh is due to improper substrate type. A further complication is that short vegetation fails to support an important beetle that preys on scale insects, with the result that scale insects can decimate marsh vegetation (Zedler and Powell, 1993). A second study (in progress at the Pacific Estuarine Research Laboratory) has demonstrated that coarse sandy substrates in a high-marsh setting failed to retain moisture needed by algae and pickleweed; hence, vascular plant establishment was slow and algal mats were slow to develop. It may well be that all of these effects are caused by a substrate that is too sandy. The evidence is sufficient to require that special attention be paid to substrate particle size, and that constructed habitats closely match the substrates of model systems.

3.4.2 Oxygen and Light

Particle size is not independent of other variables that are important to plants and animals. Where water flows rapidly over and through the sandy substrate, oxygen supplies are maintained, and sediments are less likely to become anaerobic. Species living in sand may not need to adapt to low oxygen concentrations. However, in fine muds, even when water flows over the sediment, oxygen does not readily diffuse into the soil, due to resistance. In addition, the slow-moving or stagnant water that allows fine sediments to accumulate probably also allows organic matter to accumulate, and the fine muds are likely to be rich in decomposers (bacteria and fungi that break down organic matter). Any oxygen entering the sediment will be rapidly consumed. Fine muds are thus often anaerobic, and only a few species of animals are able to flourish. Many plants are unlikely to thrive in fine mud, because light conditions will often be poor, again as a result of the slow-flowing water, which will accumulate phytoplankton more readily (thereby absorbing light before it penetrates to the sediment). Inflowing tides and bioturbation (animal burrowing activities) stir up the fine sediments and maintain a murky water column. Light conditions will be best during low tide. Macroalgae, such as *Enteromorpha* spp, are able to establish on the mud surface during times of day-time low tides, and then to float to the surface as fronds develop and oxygen accumulates in their tissues.

Because particle size distributions, sediment oxygen concentrations, and light conditions are strongly influenced by water flow rates, channel configurations are extremely important in establishing the species richness and abundance of both plants and animals. Furthermore, the relationship exists not only within the channels themselves, but also in the adjacent habitats. Vegetated marshes will trap sediments from the inflowing tides, as well as release detritus to the channels, so the nature of the marsh soil is dependent

on channel dynamics. Certainly, this is the case for stream ecosystems that support salmonids. Woody debris, which complicates the flow dynamics and stream geomorphology, significantly helps to maintain the ecosystem (Koski, 1992). For example, accumulation of sediments, from a log or other debris, can cause the formation of pools salmonids use for spawning (Koski, 1992). Resh and Balling (1983) found that shallow ditches dug to control mosquito populations at the Albrae Marsh can provide refuge for fishes such as the mosquitofish (Balling *et al.*, 1979, cited in Resh and Balling, 1983). Thus, the geomorphology of an ecosystem, which affects its hydraulics, may promote the survival of particular species. When these are endangered, as in the case of California's clapper rails, it is essential to understand the details of how topographic heterogeneity affects habitat quality.

3.4.3 Inundation, Algal Growth, and Invertebrate Use

Inundation patterns affect both algal cover and macroinvertebrate communities. Inundation threshold (the water level required to wet an area) is a physical characteristic of a channel, pothole or ditch that can be controlled in construction. Barnby *et al.* (1985) found exponential decreases in the frequency and duration of tidal inundation with linear increases in inundation threshold. Ditched study sites (potholes) were more influenced by tides due to their lower inundation thresholds, compared to unditched sites. Salinity and temperature were both more uniform, and there was little accumulation of filamentous algae in potholes with low inundation thresholds.

A shallow creek closed to tidal flushing may form algal blooms and restrict use of the habitat by fishes, while frequently flushed shallow ditches may prevent accumulation of algae. Intermediate development of algal mats can provide habitat for macroinvertebrates, providing food for some species and refuges from predators for others. For example, Rudnicki (1986, p.37) found that "algal mats in the channel and lagoon sites provided food and habitat for a few invertebrates," including the Minute Moss Beetle, but made no mention of whether this was true for tidal creeks.

At the Petaluma Marsh adjacent to San Francisco Bay, Barnby *et al.* (1985, p.343) observed that "differences in abiotic factors and algal cover" accounted for "many of the differences in macroinvertebrate community structure" among potholes. For example, the oligochaete, *Paranais litoralis* uses filamentous algae as a refuge from predators, and was found in higher densities in areas of greater algal growth. However, algae did not exclusively determine populations of *P. litoralis*. Inundation threshold also strongly affected the pothole environment. Macroinvertebrate communities were most diverse in potholes with intermediate inundation thresholds, i.e., above and below the mean higher high tides. Potholes with higher thresholds had higher salinities and provided habitat for more distinct macroinvertebrate communities, sometimes excluding large populations of *P. litoralis*, regardless of algal cover; those with lower ones supported more similar communities.

Algal cover of a tidal creek or channel varies from year to year, depending on channel size and shape, nutrient influx, tidal flushing (and extent to which propagules are washed away), and other factors. Algal

cover is important because it affects the water quality below. Water high in nutrients, especially nitrogen and phosphorus, will support large algal growths in infrequently flushed areas. According to Rudnicki (1986), nutrient addition was the most important factor affecting *Enteromorpha* yields at Tijuana Estuary, with larger additions corresponding to greater yields. If sewage spills into an estuary, then algal blooms are likely to form, consuming much of the dissolved oxygen when the algal biomass decays (Fong *et al.*, 1993; 1994). This can cause fish kills and can produce strong and unpleasant odors.

3.4.4 Proximity of Marshes and Tidal Creeks

Use of marsh surfaces by fish and free-swimming invertebrates is greater where tidal creeks are more dense and the ratio of edge to marsh is higher. There are also differences in species composition between marshes near creek edges and those further from the edge or in ponds on the marsh surface (Peterson and Turner, 1994; Baltz *et al.*, 1993; Rozas, 1992; Thomas *et al.*, 1990).

The dependence of mobile animals on tidal creeks is evident from observations of bird feeding and resting activities. Most birds are terrestrial animals that use channels only for feeding. Shorebirds have legs and beaks of different lengths (long-legged birds such as stilts have long beaks, and short-legged birds such as the smaller sandpipers have short beaks) that allow them to forage in differing water depths. As the tide moves out, the birds move onto the exposed mud or into the shallow water. When the tide is in, the birds can be found in the preferred resting areas.

Birds that nest in the tidal marshes (e.g., rails) establish home ranges that include their foraging area and nesting territory. Such species must balance the benefits of tidal creeks (food source) with the associated problems (threat of nest inundation). Belding's Savannah sparrows nest in mid-intertidal saltmarshes dominated by pickleweed (*Salicornia virginica*). They do not require tidal creeks within their nesting territories, but they seem to thrive where such features are an integral part of the saltmarsh. These birds often fly to beaches or tidal creeks to find their invertebrate foods. Obviously, the presence of a tidal creek nearby would reduce energy requirements and presumably increase nest success. However, if there is too much tidal action, the bird's nest may be threatened by inundation, especially when nests are built on the ground. If the bird accommodates the rising tide by nesting in the pickleweed canopy, it risks predation by raptors and other animals that can more readily see the eggs or chicks.

Collins and Resh (1985) studied how shallow mosquito ditches connecting tidal creeks to Petaluma Marsh affected the population of song sparrows. The ditches increased the total habitat area and population size of the sparrows. The increase in population was mainly due to the greater abundance of potential nesting habitat and food. The song sparrow favors tall (at least 54 cm) and dense vegetation for its nests, which are common in a 15-meter-wide band along each side of the tidal creeks and in a narrow band around the ditches (Collins and Resh, 1985). While the shallow ditches provided extra habitat for the nesting song sparrow, it was not considered ideal because the sparrows held larger territories and were less dense in ditched areas.

The home range of southern California's light-footed clapper rail is from 2-4 acres in size, and it includes tidal creeks, where the birds forage for crabs, snails and other foods. These birds are poor at flight, so they remain close to feeding grounds. Hence, they are tied to sites with both creeks and marsh. They nest on the ground, but elevate their nest and build it of hollow cordgrass stems so it can float when extreme high tides occur. They reduce chances of raptor predation by weaving the overhead cordgrass into a concealing canopy.

3.4.5 Marsh Vegetation near Creeks

Marsh vegetation has many linkages with creeks, and the differences between creekside and marsh plain vegetation have been quantified by various wetland scientists (e.g., Bradley and Morris, 1990). Creek edges are extremely productive because of the circulation provided by flowing water. Sediments are more readily oxygenated, salinities are more stable at lower intertidal elevations, more nutrients are supplied, and toxic materials washed away. Anoxia is less likely to develop, so sulfides do not build up and nitrogen may be taken up more readily.

Nitrogen is a controlling variable for saltmarsh vegetation, and its dynamics may be both a direct and indirect function of tidal flow. Inputs of inorganic nitrogen are provided by tidal waters, and outputs of organic nitrogen are likely. Within the sediments, the alternation between oxygenated and anoxic conditions, which accompanies the rise and fall of tidal waters, enhances de-nitrification. It may also enhance nitrogen fixation by blue-green algae and bacteria at the marsh surface. The net effect of nitrogen inputs and outputs from these two processes has rarely been studied.

3.4.6 Depositional vs. Erosional Banks

McIvor and Odum (1988) compared nekton use of marshes fed by tidal channels that differed in geomorphology. Marsh surfaces that were adjacent to depositional banks supported more nekton than marsh surfaces next to steeper erosional banks. They attributed the higher numbers to two attributes of the depositional environment, which they assessed experimentally: fewer predators and greater food availability. They found that depositional banks supported a greater biomass of invertebrates, although erosional banks had more individuals. On the depositional banks, amphipods were especially abundant; on erosional banks, chironomids and harpacticoid copepods were much more abundant. In general, they concluded that small fishes and grass shrimp seemed to prefer densely vegetated areas next to depositional creek banks to marshland adjacent to erosional banks during the flood tide. "Three species of juvenile fishes chose shallow riffles and raceways in a semi-natural artificial stream when predators were present in deeper pools, even though the shallow habitats were more energy-expensive" (McIvor and Odum, 1988).

Marshes adjacent to second and third order channels supported more fish than those next to rivers (Weinstein 1979, cited in McIvor and Rozas, in review). In this case, the proposed cause was greater abundance of submerged aquatic vegetation. Additional attributes of the marshes that were found important to fish support-functions were duration of marsh submergence and proximity to subtidal channels (channel density or drainage density).

In Petaluma Marsh, adjacent to San Francisco Bay, Barnby *et al.* (1985) found that the differences between environments of natural potholes and shallower man-made ones significantly affected macroinvertebrate diversity, though macroinvertebrate populations were similar between the ditched and natural sites. Temperature variations were much larger in ditched than natural potholes, mostly because of their shallower depth. They found that "differences in macroinvertebrate community structure...were due to differences in abiotic factors and algal cover..." (Barnby *et al.*, 1985, p. 343). The basic effect of ditching potholes is the simplification of the macroinvertebrate community by both decreasing its diversity and increasing its similarity between different potholes; this is mainly due to lower inundation thresholds.

3.4.7 Habitat Patch Size and Shape

The "landscape ecology" approach is just being developed for tidal wetlands. Scientists have not yet quantified marsh patch sizes, shapes, connectivity, or topographic variability for many marshes.

The relationships of marsh patch size to creek size and length of "edge" have not been determined for many marshes. Those already established depend at least on the general marsh structure and tidal energy inputs, indicating that there is no universal law governing the geomorphology of tidal creeks. Thus, such relationships may be specific to region, soil types or other factors that vary from marsh to marsh. Steers (p.45, 1977) stresses the importance of attention to details of a marsh, i.e., "the tides, the type, and means of sedimentation, the floor on which the sediments rest, the slope of this floor and the irregularities on it, the spread of vegetation and other factors."

The light-footed clapper rail is a good case study, because its specific needs have thus far precluded marsh designers from achieving suitable habitat. Since it requires channels for food, marsh for nesting, and high marsh as a high tide refuge, designing habitat for this species is not simple. Each 2- to 4-acre home range must be adjacent to both high ground and tidal channels. Whether the high ground can be an island within the low marsh rather than a transition to upland is unknown. Whether the channel must abut rather than dissect the home range is unclear. The birds can swim or fly across channels, but their preferences are not known.

Habitat islands that were created at San Diego Bay appear to have the wrong shape and perhaps are too small to provide suitable topographic complexity. Several islands, each under an acre were designed to have high marsh in the middle and cordgrass around the edge. This mandated a fairly steep slope leading

up to the high marsh. While cordgrass has established around the periphery, the "domes" have mostly failed to become vegetated. Salt accumulation appears to be responsible for the bare tops, but it is not clear what is responsible for the salt crusts, as the elevation is appropriate for high marsh vegetation. Perhaps the rounded topography makes each dome act as a wick. Alternatively, the sediment may be too compacted for plants to establish. Perhaps the long, narrow site was unsuitable for such a complicated topographic requirement--maybe a central channel that provided high marsh at the wetland-upland interface would have been better than a system of islands. The point is that the cause of the bare domes needs to be known so that future marsh designs can avoid similar problems.

3.4.8 Summary of Important Ecological Factors in Tidal Channel Design

Although many factors affect species abundances and ecosystem functioning, an attempt has been made to summarize the effects of geomorphologic characteristics. Table 3.4.8-1 should help guide the construction of channels to support the natural biodiversity.

TABLE 3.4.8-1

ECOLOGICAL DESIGN GUIDELINES FOR TIDAL CHANNELS

<i>Channel Depth:</i>	Should not be much lower than natural nearby creeks, unless the purpose of ditching is to control mosquitoes. Channels leading to potholes should have intermediate depth (about MHHW) to maximize faunal diversity, according to studies of Petaluma Marsh in San Francisco Bay. Potholes above mean higher high tide, have widely varying environmental conditions with infrequent inundation, which increases salinities and simplifies the structure of macroinvertebrate communities. Much lower inundation thresholds provide habitats that vary little and are similar to one another.
<i>Tidal Creek Flushing:</i>	Intermediate levels of tidal flushing in small creeks should allow algae to grow, while preventing the formation of excessive algal blooms. Well-flushed creeks tend not to support macroalgae, while stagnant creeks support algal blooms that do not support fish and invertebrates.
<i>Sediment Particle Size:</i>	For maximum biodiversity, a wide range of substrates is desirable, as individual species prefer different types. Muds that are too fine tend to have low concentrations of oxygen and support fewer animals; coarser mud or finer sand provides better habitat for attached' and burrowing organisms. Channels with sandy bottoms favor flatfishes and support more fish species at Tijuana Estuary.
<i>Creek Density:</i>	Most marshes seem to have a region dense in channel habitat to dissipate energy efficiently. Fish seem to prefer marshes with greater density of tidal creeks. Tidal creeks provide food for birds. The regions near their edges support high and dense vegetation, in general higher and denser than found on the marsh plains, which can serve as vital nesting habitat. However, it is not clear whether a highly sinuous creek or a branched creek would be more effective to support fish or bird communities.
<i>Channel Profile:</i>	Depositional banks supported larger communities of nekton than did steeper erosional banks in Virginia (McIvor and Odum 1988), mainly because of fewer predators and greater food availability. Small fishes and grass shrimp seemed to prefer densely vegetated areas next to depositional creek bands to marshland adjacent to erosional banks during the flood tide. However, steeper banks may be inhabited by different plants than depositional banks, creating habitats for different fishes, birds and invertebrates. For example, in San Francisco Bay, <i>Salicornia virginica</i> thrives in and helps create steep, undercut channels, whereas <i>Spartina foliosa</i> tends to grow in shallower ones (Steers, 1977).

4. ENGINEERING GOALS

Although the creation of channels in a tidal marsh may be driven by the ecological goals and criteria, those goals must be translated into engineering goals. The defined engineering goals for a project may include:

- ***Levee breaching***
In some cases, the only part of the channel system that needs design is the opening in a levee between a tidal system and an isolated diked area. In such a case, the engineer will need to know how deep and wide the opening in the levee should be.
- ***Excavation of channels***
In some cases, it may be desirable to excavate a channel system into old dredged material, or to excavate an inlet channel to a potential marsh system. The channel systems must be large enough to provide adequate tidal flows to the restored marsh.
- ***Navigation***
Tidal creek channels are often used for navigation, especially by small recreational boats. With adequate tidal prism, a channel can be designed to maintain itself, without the necessity of expensive dredging. Rather than determining how big a channel is needed for a given tidal prism, this problem asks: how much tidal prism is needed to maintain a channel of a given size?
- ***Flood Control***
It is possible in some cases to maintain flood control channels free of sediment by taking advantage of the natural scouring potential of a tidal wetland. Restoring tidal action to a diked area near the mouth of a flood control channel increases the tidal prism and velocity of tidal flow in the channel. This approach has been used successfully at Huntington Beach (in Southern California) and San Leandro (San Francisco Bay).
- ***Disposal of Dredged Material***
Wetland creation is sometimes an adjunct of the disposal of dredged material (Landin, 1993; U.S. Army Corps of Engineers, 1986). In such cases, it is important that the wetland restoration be planned contemporaneously with the dredged material disposal project. The final elevation of the dredged material has a strong influence on subsequent channel formation as well as on the type of habitat that results. The possibility of using natural tidal action to create small slough channels is discussed below.

5. HYDRAULIC GEOMETRY RELATIONSHIPS AND REGIME EQUATIONS IN TIDAL SLOUGH CHANNELS

At a given cross section in a river channel, there are mathematical relationships between discharge (Q) and velocity, width and average depth. These relationships, originally called "regime equations", have been used since Lacy (1929) showed how they could be used for design of irrigation canals. Leopold and Maddock (1953) introduced the idea to the field of fluvial geomorphology, calling the relationships the hydraulic geometry. The relationships may be defined as follows:

$$w = aQ^b$$

$$d = cQ^f$$

$$u = kQ^m$$

where

Q	=	discharge
w	=	width
d	=	average depth
u	=	velocity

$a, c,$ and k are constant coefficients
 $b, f,$ and m are constant exponents.

Since discharge is the product of area and velocity,

$$Q = Au = wdu$$

and

$$Q = (aQ^b)(cQ^f)(kQ^m)$$

and

$$b + f + m = 1$$

$$a \times c \times k = 1$$

On a log-log plot the exponents $b, f,$ and m represent the slopes of the relationships between discharge, and width, depth and velocity.

Myrick and Leopold (1963) applied these relationships to tidal slough channels, and found that the values for b , f and m depended on whether the velocity was increasing or decreasing, and whether the tide was rising or falling. Subsequent studies by other authors have begun to develop a body of literature on the values of b , f and m (see Leopold *et al.*, 1993; Siegel, 1993; Zeff, 1988). These studies of at-a-station hydraulic geometry have generally found that in estuaries, velocity changes more rapidly with discharge, and width and depth less rapidly with discharge than in terrestrial rivers.

The assumption has generally been made that the relationships are linear on a log-log plot, but Chantler (1974) showed that a plot of width (w) vs. discharge (in a downstream direction) is concave upward, whereas a plot of depth (d) vs. discharge is concave downward. The result is that a plot of wd , or cross sectional area, vs. discharge is more-or-less a straight line.

Hydraulic geometry in slough channels can also be plotted in a downstream direction, to express the way in which width, depth and velocity change with distance downstream. In order to do this, it is important to choose a representative discharge that can be applied at all cross sections. The most logical discharge to use would be the dominant, or channel-forming discharge. This is the discharge that does most of the work of carrying sediment and shaping the channel in the long run. In rivers it is thought to occur on average about two years out of three, and to be roughly equivalent to bankful discharge (Dunne & Leopold, 1978). In a tidal slough, the dominant discharge is not immediately obvious, and bankful flow can occur twice per day, on the rising and falling limbs of the tide cycle, or not at all during neap tides. Myrick and Leopold (1963) got around this problem when relating to tidal channels by defining the dominant discharge as the discharge that occurs at the time of maximum velocity, averaged for ebb and flood tides. They then measured the downstream hydraulic geometry exponents with values derived theoretically from geomorphic and hydraulic principles, and found good agreement.

In order to measure the hydraulic geometry exponents, it is necessary to measure discharge at several times in a tide cycle at a surveyed cross section, or measure discharge at the same stage in the tide cycle for several cross sections. In a practical sense this is difficult, and it is not clear how the data can be used directly in the design of slough channels in constructed tidal marshes. Tidal prism, however, can be used as a surrogate for discharge, and related to channel cross section characteristics (Williams and Harvey, 1983; Haltiner and Williams, 1987).

The volume of water exchanged over a tidal cycle in a lagoon or estuary is a major factor in determining the width and depth at a given cross section. Over time, the geometry at a cross section evolves to some equilibrium cross sectional area, width and depth. If sediment is deposited on a channel bottom during a neap tide cycle, the velocity and bed shear stress during a mean or spring tidal cycle will be slightly increased, and the deposited sediment will be scoured (French and Stoddart, 1992). If part of an estuary system is filled or diked, the tidal prism will be reduced, and the downstream channel will accumulate sediment and lose cross sectional area. This relationship assumes that there is some effective discharge, or channel-forming flow, although it not clear what that effective discharge is, or what is the tidal prism that is associated with the effective discharge.

Tidal prism is the volume of water in a marsh system contained between two defined tidal datums. It is important to distinguish between the potential and actual tidal prisms in a marsh or coastal lagoon. The potential tidal prism is a morphometric definition and is determined by the defined tidal elevations at the tidal boundary, that is, at the mouth of the lagoon or slough channel. Due to the lag and attenuation of the tidal wave in the marsh or lagoon system, the actual tidal prism, or the volume of water that moves in and out on a tidal cycle, is somewhat less than the potential tidal prism. Different investigators have defined the tidal prism in different ways:

- ***Mean Tidal Prism***

This is the volume of water in a lagoon or estuary between the elevations of Mean High Water and Mean Low Water. This variable was used by Jarrett (1976) to examine the entrance and closure conditions of coastal lagoons. In most marshes, this would include only the volume of water within channels.

- ***Diurnal Tidal Prism***

This is the volume of water between Mean Higher High Water (MHHW) and Mean Lower Low Water (MLLW). This measure is more appropriate with semidiurnal unequal tides, where there are two high and two low waters each day. Since the bankful stage in tidal creeks often corresponds roughly to the elevation of MHHW, discharge associated with the Diurnal Tidal Prism might be thought of as analogous to the bankful discharge of rivers.

- ***Spring Tidal Prism***

This is the volume between the annual average of the spring high and spring low tides, that is, the two highest and two lowest tides that occur each month.

5.1 THE SEARCH FOR A HYDRAULIC GEOMETRY DATA BASE

A major objective of this study was to find comparable data sets for different regions that quantify the relationships between tidal prism and channel cross sectional characteristics. Although a number of investigators have presented data on discharge, tidal prism or cross sectional characteristics, the published studies have all used somewhat different methodologies and different definitions, to such an extent that quantitative comparisons across different data sets are meaningless.

Tidal prism-inlet area relationships have been used to approach a number of problems in coastal engineering and geomorphology. Jarrett (1976) plotted relationships between tidal prism and the cross

sectional area below MSL of stable inlets, with and without jetties, for the Atlantic, Gulf and Pacific Coasts. This work, extending the earlier work of O'Brien (1931) and Johnson (1973), provided an empirical basis for determining the minimum tidal prism needed to keep open an inlet or coastal lagoon. Inlet closure in the cases studied by these investigators was strongly influenced by wave action and sand transport, and so these relationships cannot be applied to tidal marshes, where wave energy is generally not a factor in channel dimension.

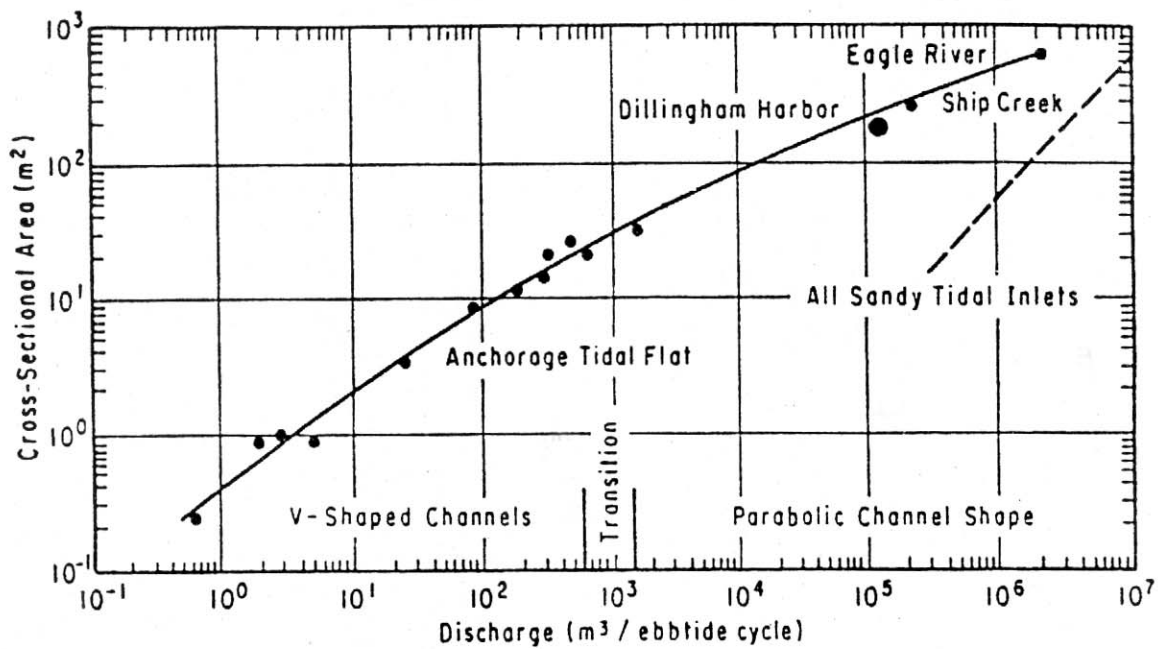
Everts (1980) plotted cross sectional area against tidal prism for tidal channels in Alaska, in order to predict the stable geometry of channels connecting enclosed harbors and navigable waters. Ebb discharge (or tidal prism) was defined as the volume between MLLW and 22 ft above MLLW; the mean diurnal range at the site is 28.8 ft and it is not clear why the tidal prism between 0 and 22 ft MLLW datum was used. Figure 5.1-1 shows the relationship developed. This relationship could be used in macro-tidal estuaries, but it is difficult to compare with other data sets. Everts noted that sediment composition (channel erodibility) is a key variable in predicting channel cross sectional area; sediment in the tidal channels used in his study was predominantly silt, with less than 2 percent clay.

In a study of marshes (fresh, brackish and salt) in the eastern U.S., Garofalo (1980) developed a table showing average width and depth in relation to discharge. The latter was calculated from tide charts showing current velocity. Figure 5.1-2 shows the cross sectional area of channels in this data set (the product of average width and average depth) plotted against "Discharge". As the hydraulic geometry theory predicts, there is a positive relationship, but there is no way to convert the discharge estimates to tidal prism estimates, and the mean discharge does not represent discharge as it is used in calculation of the hydraulic geometry coefficients.

In a study of a Virginia saltmarsh, Boon (1975) developed a hypometric curve for the marsh, which provides a basis for calculating the tidal prism. He then measured discharge and velocity at a cross section over several tidal cycles. His plot of maximum velocity vs. maximum discharge suggests that at bankful stage, the cross sectional area of the channel was about 143 ft² and the corresponding tidal prism was about 18.2 ac-ft. The study is much more useful for its elucidation of tidal hydraulics than for its contribution to a data set on tidal prism and channel cross sectional characteristics.

Data given in Leopold *et al.* (1993) allow calculation of the tidal prism in the main stem of a slough system, and this can be related to a cross section. Since tributary channels are not included, however, comparison with other studies is difficult.

Other papers reviewed in the search for a data set include: Bayless-Smith *et al.* (1979), Chantler (1974), Collins *et al.* (1987), French and Stoddart (1992), Pestrone (1965), Pethick (1980), Reed (1988), Zeff (1988), Green *et al.*, Ashley and Zeff (1988), and Healey *et al.* (1981). While many of these papers are useful for understanding tidal hydraulics (particularly the ebb-flood velocity asymmetry), they do not provide much help in terms of building a data set and tidal prism-cross section relationships.



Developed for certain tidal channels cut in compacted mud and silt-sized sediment.

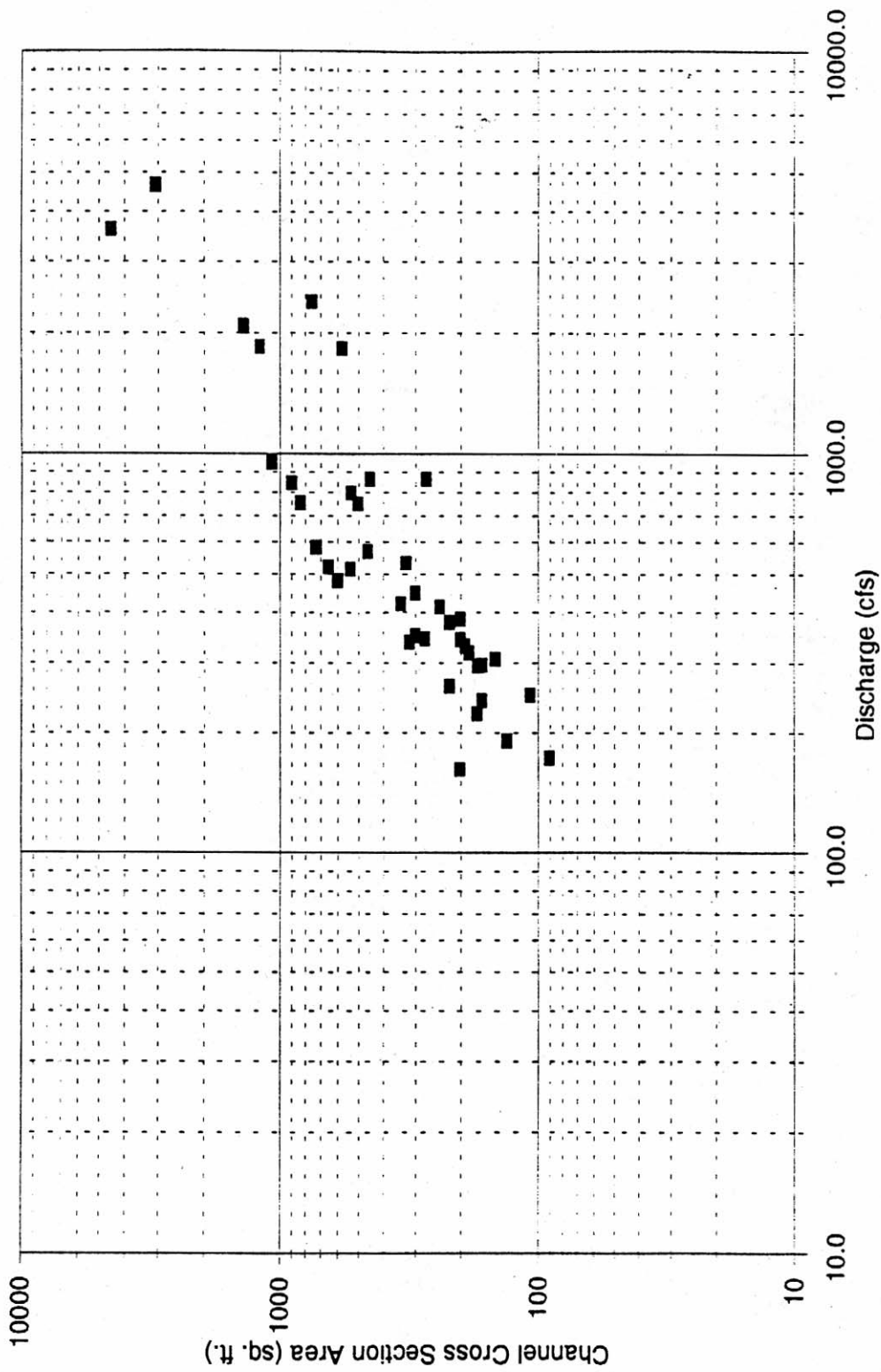
Tidal inlet curve is from Jarrett (1976).
Figure from Everts, (1980).



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Channel Area-Ebb-Tide
Discharge Relationship

Figure
5.1-1



CKCHYDGEOM8-94GAROFALO WB1VA-VS-DSCH311-31-95

Source: Garofalo, 1980



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CHANNEL CROSS SECTIONAL AREA VS.
MEAN DISCHARGE IN TIDAL SLOUGHS

FIGURE
5.1-2

5.2 A TIDAL PRISM-CROSS SECTION DATA SET FROM CALIFORNIA

In order to provide a basis for channel design, cross section and topographic data were collected from several tidal saltmarshes in coastal California. The tidal regime in the marshes studied is semidiurnal, with a range that varied from 4.3 to 8.4 ft. Cross sectional area, and maximum depth were measured below the elevation of MHHW; channel width was measured at the elevation of MHHW. In a few cases where top of the channel bank was below the elevation of MHHW, the top of bank was projected vertically upward to the elevation of MHHW to provide a basis for measurement, and storage volume on the marsh plain was added separately. Appendix I describes the marshes that were included in the study.

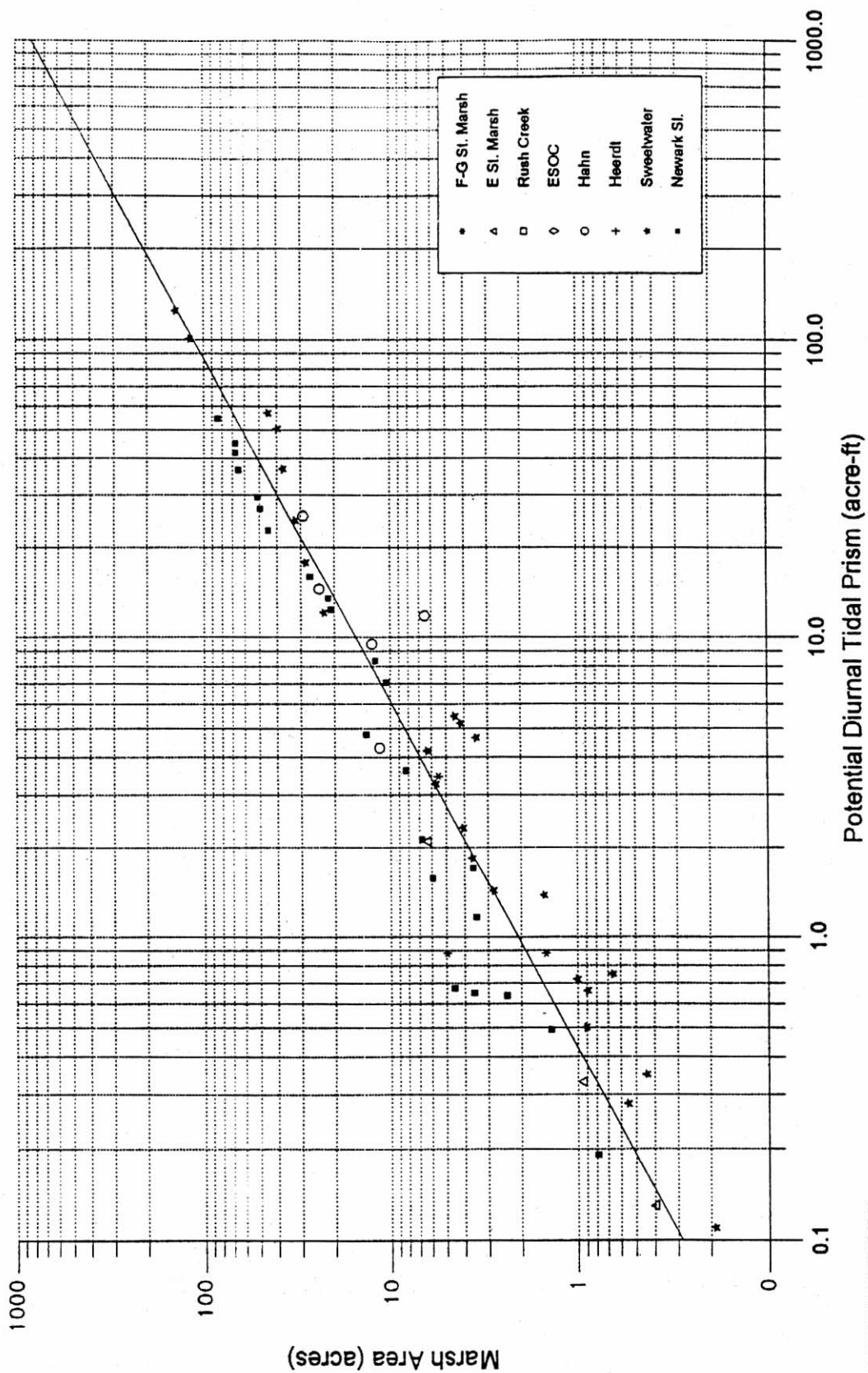
Marsh area was measured upstream (landward) of each cross section on the topographic maps by delineating apparent drainage boundaries between slough tributary systems. There is some uncertainty in such a delineation, since tidal flow in a marsh can enter through one tributary and ebb through another.

The Potential Diurnal Tidal Prism associated with each cross section was measured using topographic maps (generally at scale of 1:1200 with 1 ft contour intervals) and surveyed upstream cross sections; the volume between cross sections was then calculated using the formula for the volume of a cone frustum.

Close inspection of the data points suggests that the data set is not homogeneous. The channel depth and cross sectional area for channels in the Newark Marsh, for example, plot a little higher (for given tidal prism) than data from the other marshes. This may be due to the higher tidal range at that site (8.4 ft Mean Diurnal Range). Other variables that may contribute to variability in the data set include marsh age, sediment size and vegetation. The data set should be considered provisional; as additional data become available, especially for marshes with different tidal regimes, these relationships can be refined.

Figures 5.2-1 to 5.2-5 show the graphical plots of the Potential Diurnal Tidal Prism data set. These relationships can be used to develop a first approximation for design of a tidal channel. For example, if a diked area is to be opened to tidal action, the open volume behind the dike between MHHW and MLLW can be measured, and the appropriate graphs used to estimate the required maximum channel depth, cross sectional area and width at MHHW. If only the area of a marsh is known, the Area-Tidal Prism relationship can be used to find an approximate value for Potential Diurnal Tidal Prism. Section 9.2 (below) illustrates some potential applications of the relationships in solving design problems

Of the variables width, depth and cross sectional area, the latter two are relatively easy to define and measure in the field. Width, however, is more difficult to define at a cross section if the apparent top of the bank is below the elevation of MHHW. Where the bank of a channel slopes gradually up toward the marsh plain, the "top of bank" is taken to be at the point of the sharpest break in slope on the channel bank, and width is measured from the vertical projection of this point up to the plane of MHHW (usually less than 0.5 ft). Any uncertainty about defining the top width of the channel has almost no effect on the



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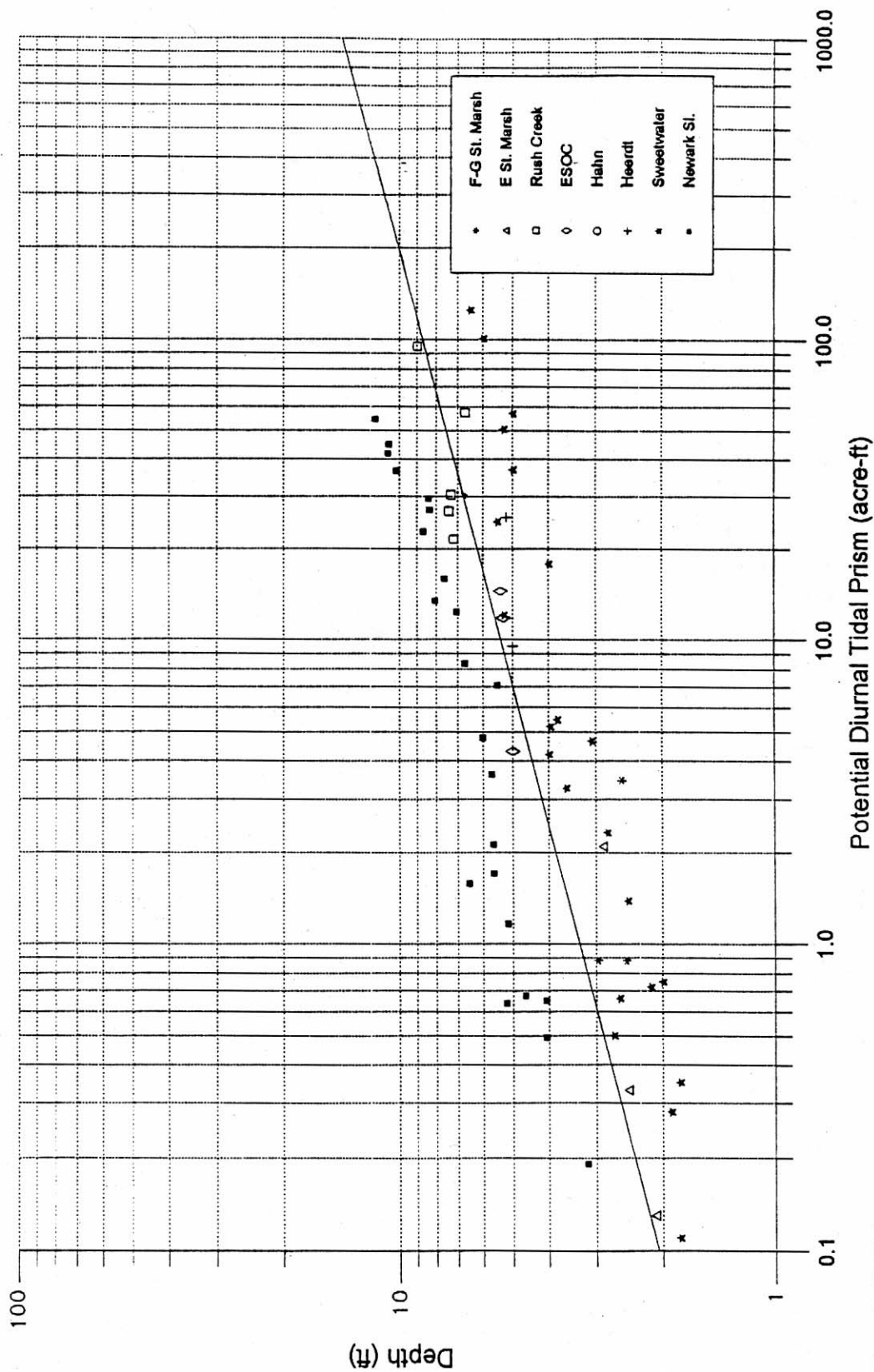


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MARSH AREA VS. TIDAL PRISM IN TIDAL SLOUGHS

FIGURE
5.2-1



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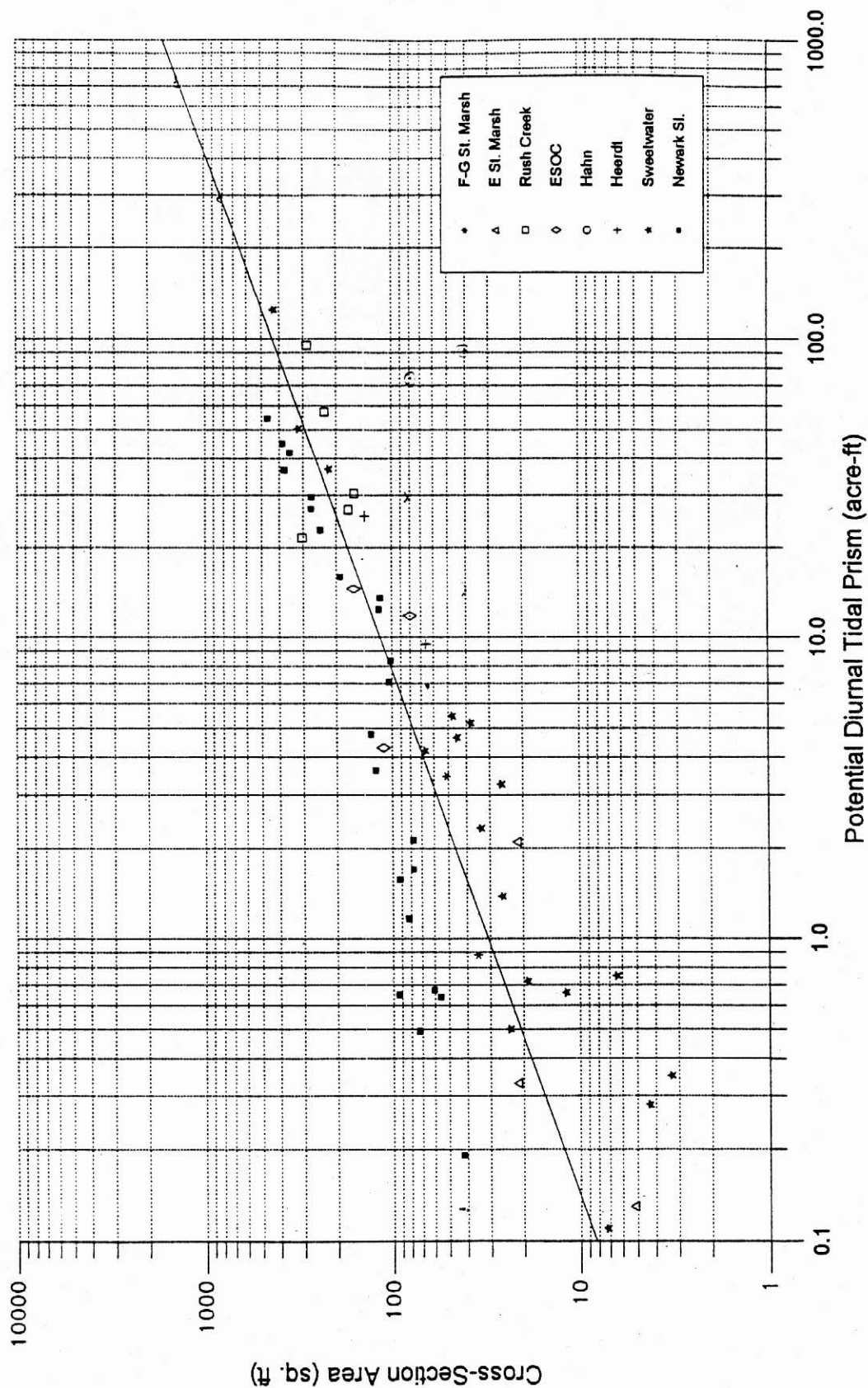
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FIGURE

5.2-2

MAXIMUM DEPTH VS. TIDAL
PRISM IN TIDAL SLOUGHS



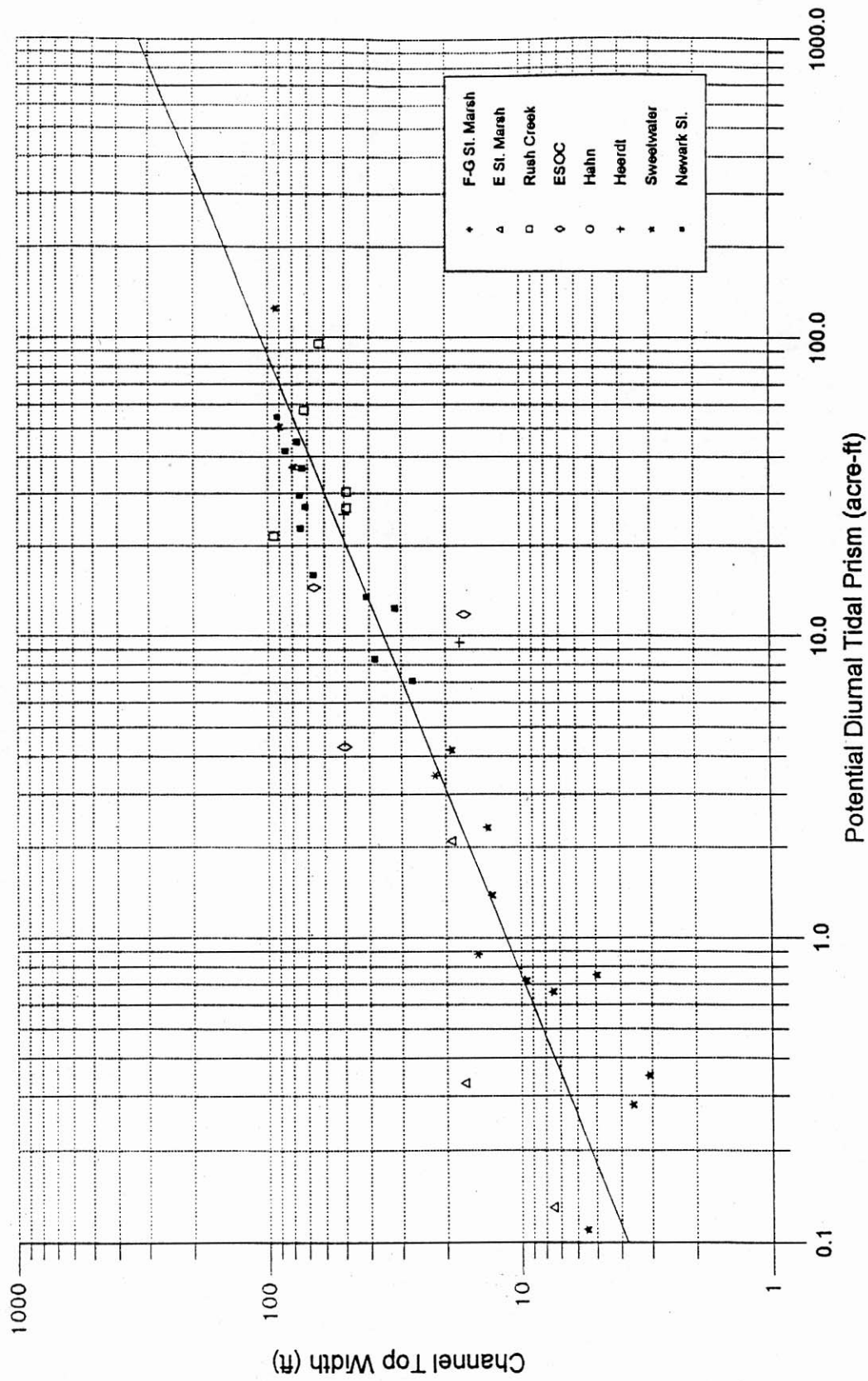
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CHANNEL CROSS-SECTIONAL AREA VS.
TIDAL PRISM IN TIDAL SLOUGHS



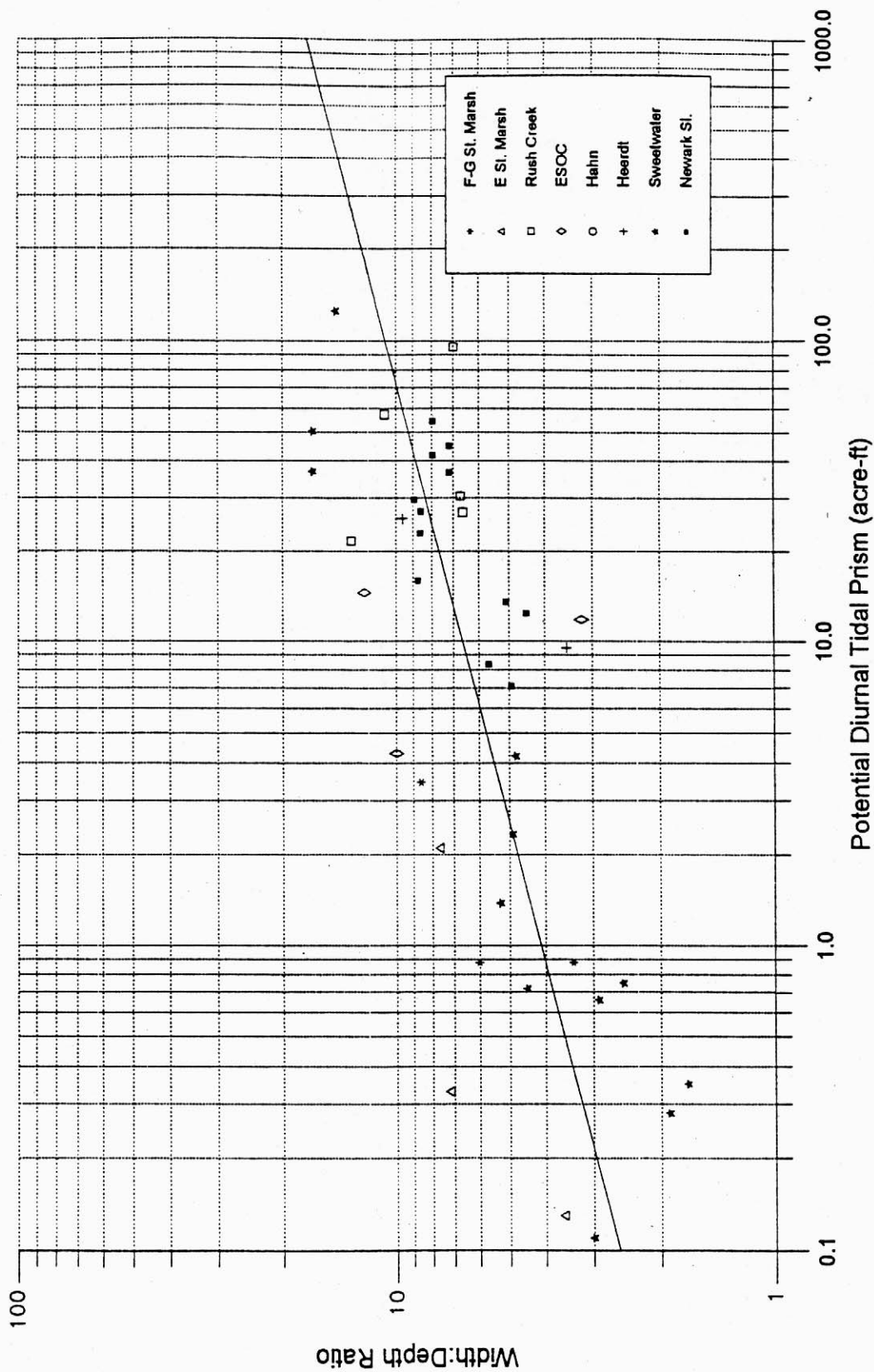
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CHANNEL TOP WIDTH VS.
TIDAL PRISM IN TIDAL SLOUGHS

FIGURE
5.2-4



2KCHYDGEOMTRWD94K GR1/7-27-94



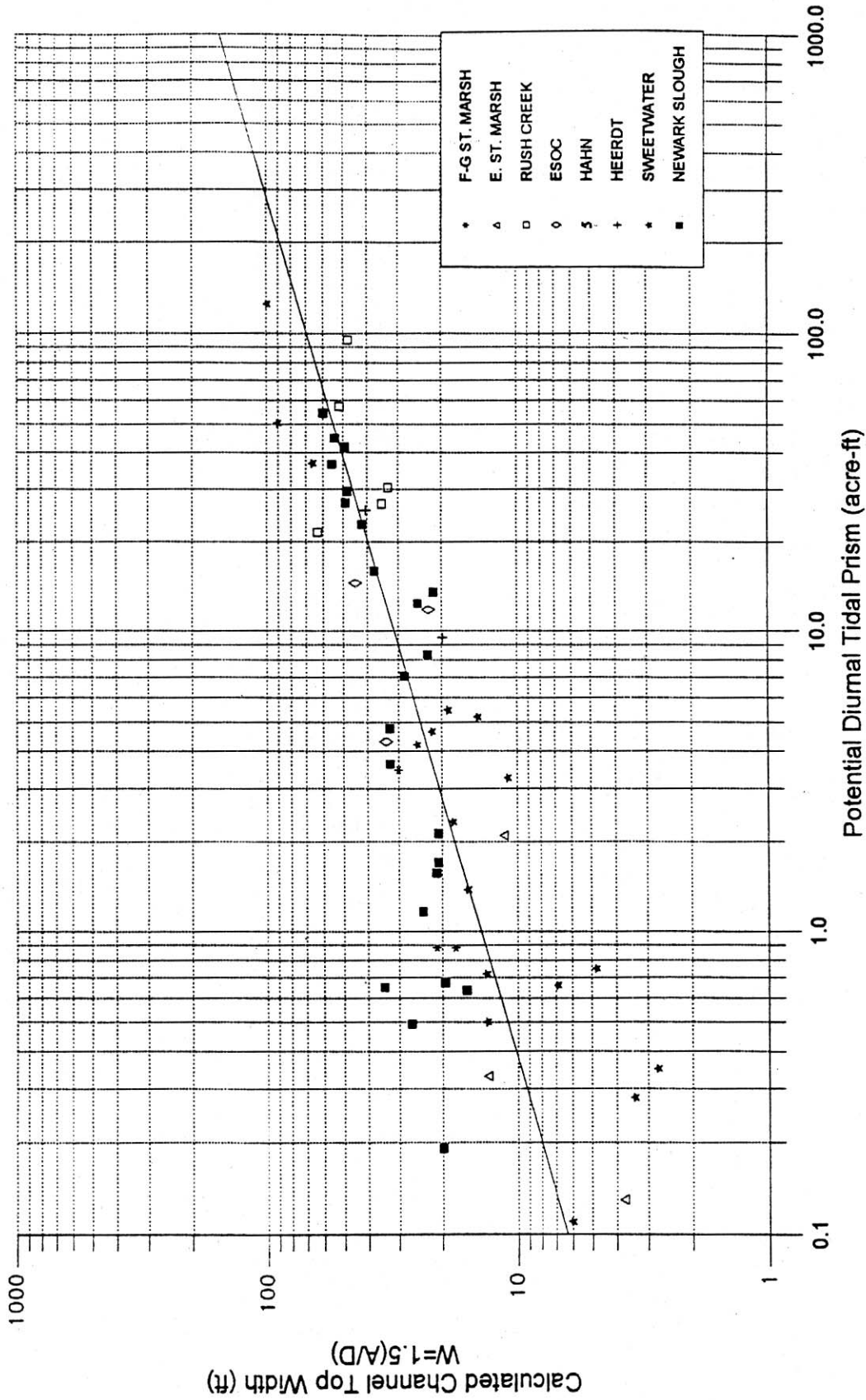
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WIDTH:DEPTH RATIO VS.
TIDAL PRISM IN TIDAL SLOUGHS

FIGURE
5.2-5



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FIGURE

5.2-6

CALCULATED CHANNEL TOP WIDTH
VS. TIDAL PRISM IN TIDAL SLOUGHS

measurement cross sectional area, however, since virtually all of the channel conveyance is below the break in slope at the top of the bank.

The plots of width, depth and cross sectional area against tidal prism define a channel bottom width and side slopes, if the channel is assumed to be trapezoidal. The channel shape, however, is not consistent over the range of data included in the data set. An alternative approach is to assume that channels have a consistent parabolic shape, and use the formula for the area of a parabolic channel

$$w = \frac{1.5A}{d}$$

to calculate top width (w) as a function of cross sectional area (A) and maximum depth (d), for each cross section. Figure 5.2-6 shows the results. This provides a consistent definition of width, depth, and cross sectional area required for a given Potential Diurnal Tidal Prism volume.

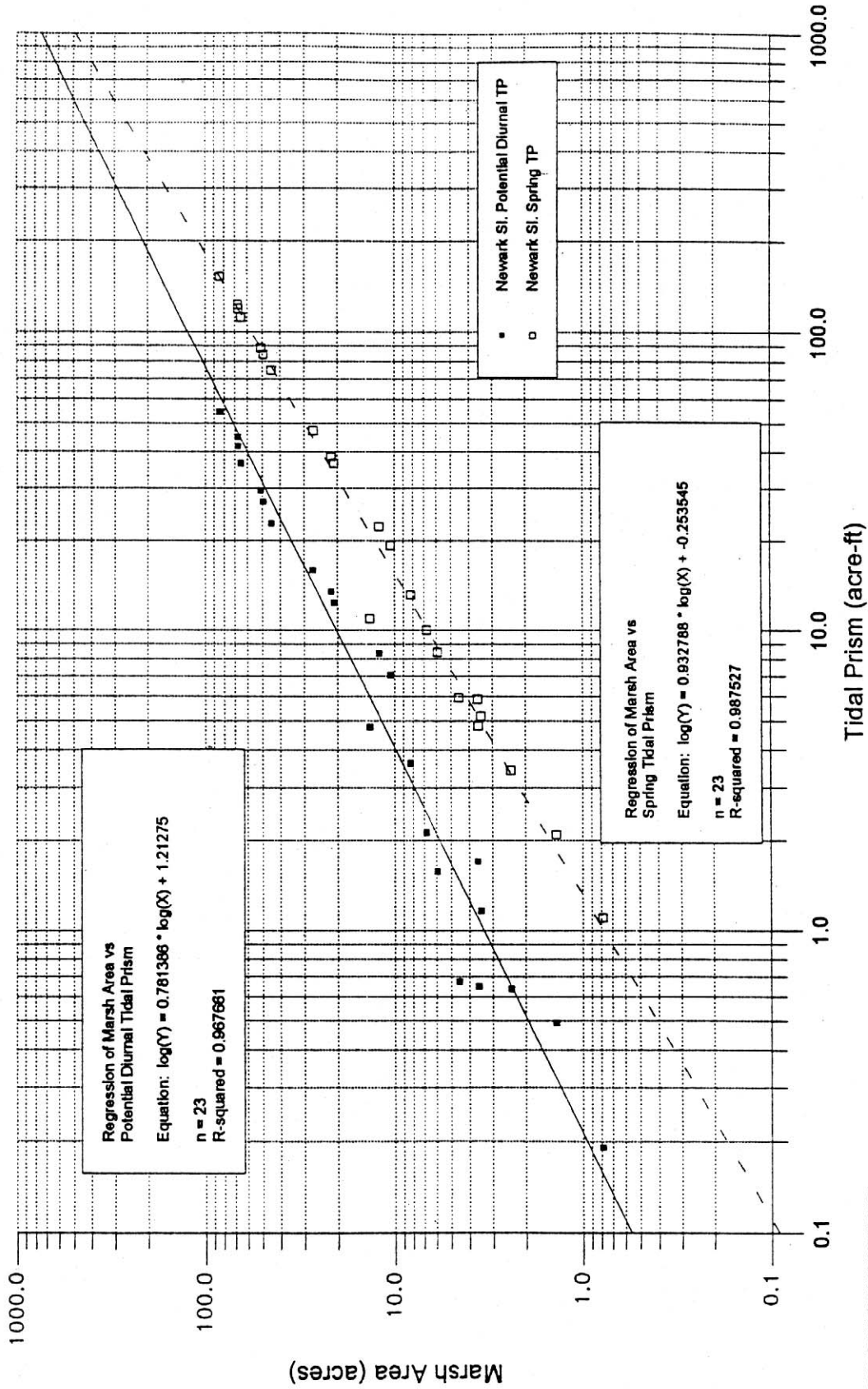
These relationships should be applied with considerable caution where the Diurnal Range is less than 4.3 or greater than 8.4 ft. Caution should also be exercised in extrapolating the relationships beyond the plotted data. These relationships should be applicable to the East Coast and Gulf Coast as well as the West Coast, since they are based on basic geomorphic processes. It is worth noting that the data point derived from Boon (1975) for cross sectional area (143 ft²) and tidal prism (18.2 ac-ft) plots virtually on the regression line for the California data set (Figure 5.2-3). The relationships should, however, be verified (and adjusted) with local data from a reference site that closely matches a project site in terms of sediment characteristics and vegetation.

Although the Potential Diurnal Tidal Prism is convenient to use, there are good arguments for using some higher tidal prism, such as the Potential Spring Tidal Prism. A number of investigators have shown that tidal channels are characterized by two flow regimes (French and Stoddart, 1992; Pestrong, 1965; Boon, 1975; Pethick, 1980). Below-marsh tides are associated with relatively moderate discharges and velocities, with slightly higher mean velocities on the flood tide. Above marsh tides are characterized by velocity transients or pulses; maximum velocity may exceed that of below-marsh tides by a factor of 3 or 4. The flood tide pulse occurs with the sudden increase in tidal prism as the tide begins flowing over the marsh plain; the ebb-tide pulse occurs as flow draining off the marsh plain converges toward the channels (French and Stoddart, 1992). During astronomical tides, the ebb velocity pulse is greater and of longer duration than the flood pulse, although in storm surges, the opposite may be true (Bayliss-Smith *et al.*, 1979). It seems likely then, that the geomorphically-effective tide is one that floods the marsh plain, and is somewhat greater than MHHW.

Bayliss-Smith *et al.* (1979) found that the threshold tide for an ebb-tide velocity pulse inundated the marsh plain to a depth of about 20 cm. Such a tide is somewhat lower than the mean spring high tide in many marshes. The mean spring high tide is the average of the highest tides associated with the full and

new phases of the moon, that is, the average of the two highest tides per month. Its frequency (as higher high water) is about 0.07, and its elevation can be calculated if a tidal frequency curve is available (Harris, 1981).

In order to compare the spring tidal prism with the diurnal tidal prism as the independent variable, the data for one marsh (Audubon Marsh, in San Francisco Bay) were plotted using both relationships. Figures 5.2-7 to 5.2-11 show the results. Using the spring rather than the diurnal tidal prism makes a slight but hardly significant improvement in the R^2 values, since the two variables are themselves so highly correlated. Although the spring tides are probably responsible for doing more of the work of forming and maintaining channels than the average tides, the Potential Mean Diurnal Tidal Prism is satisfactory to use as the independent variable, and offers the advantage of simplicity and ease of definition.



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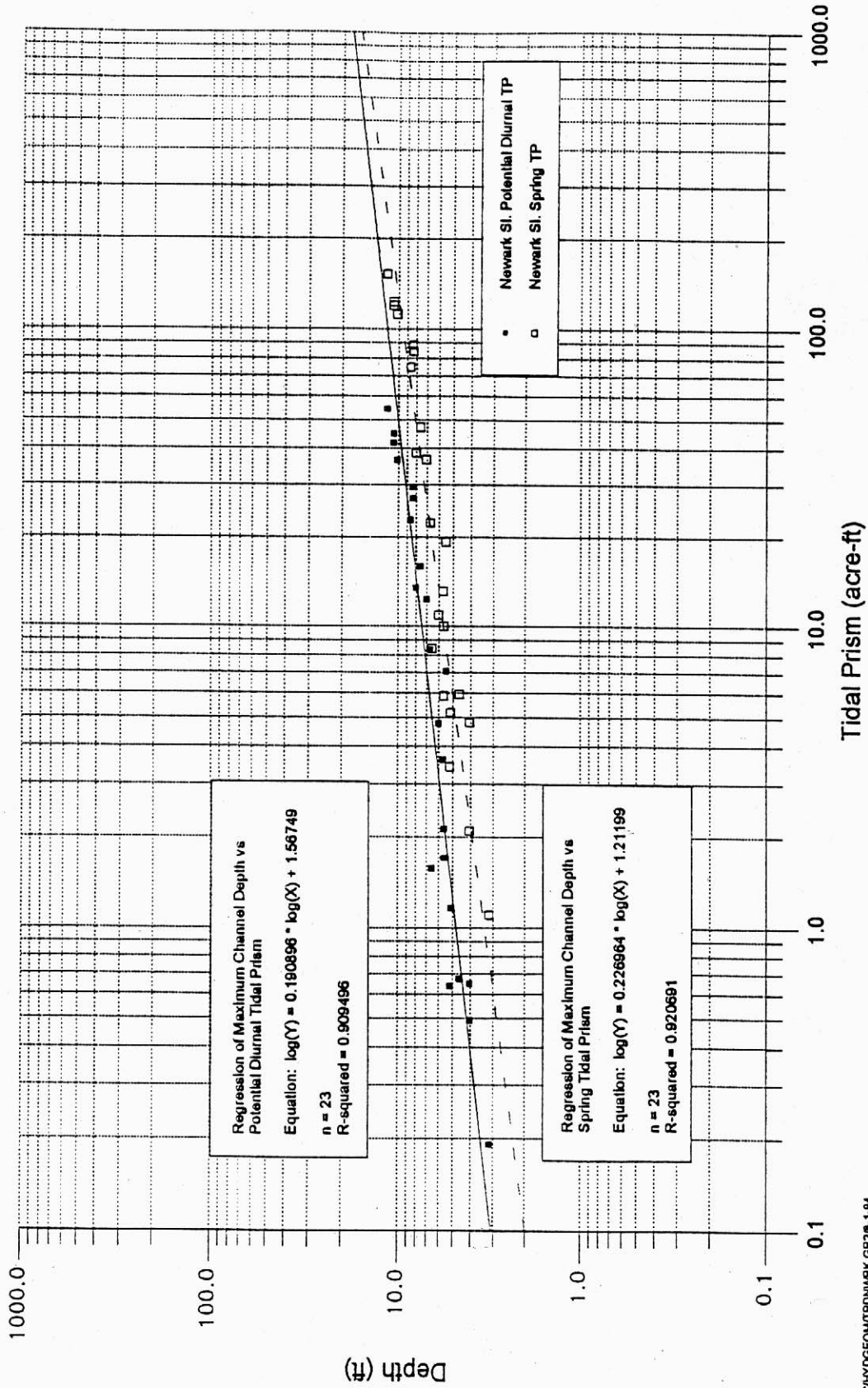
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**MARSH AREA VS.
TIDAL PRISM IN TIDAL SLOUGHS
AT NEWARK SLOUGH (AUDUBON MARSH)**

**FIGURE
5.2-7**



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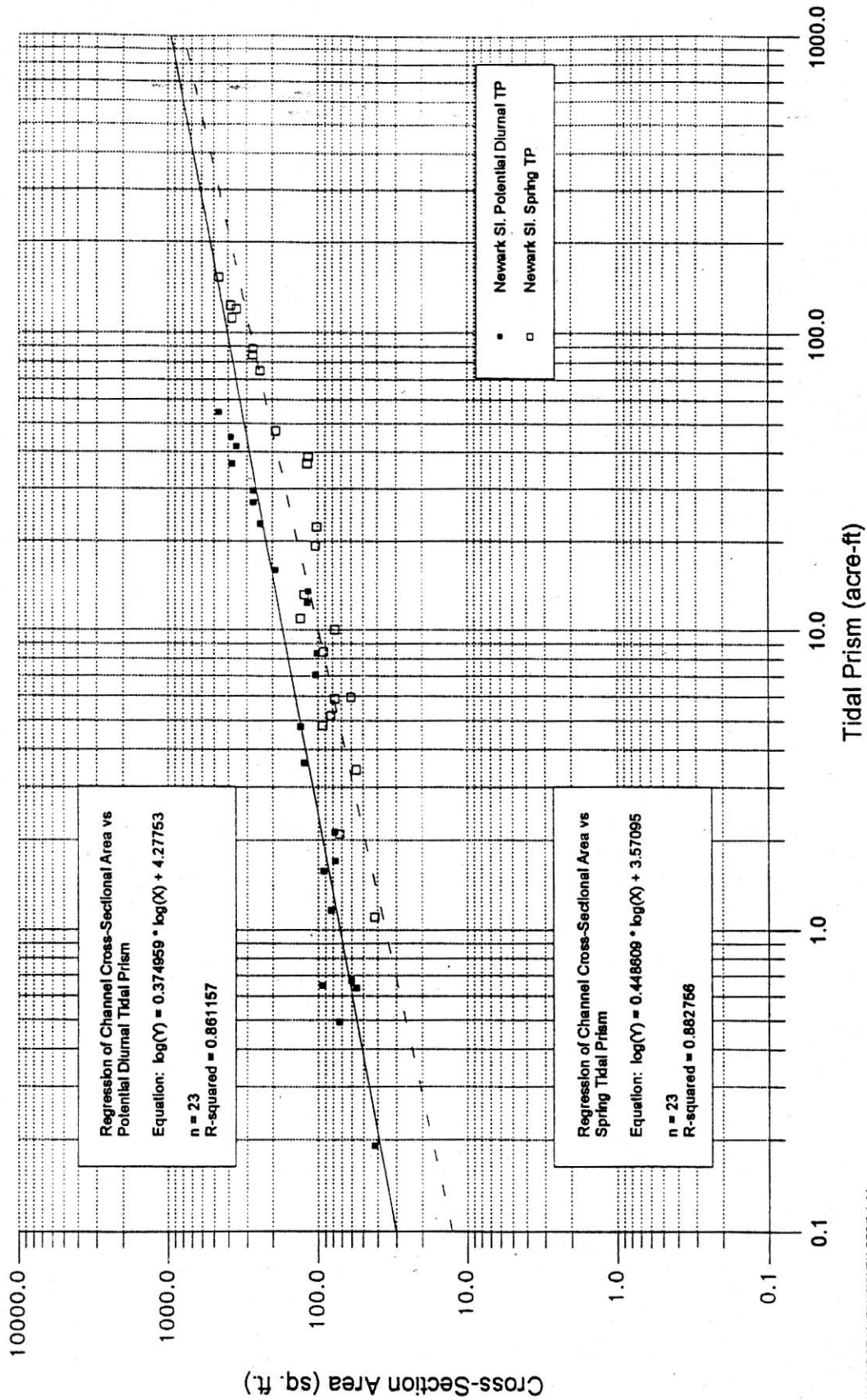


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MAXIMUM CHANNEL DEPTH VS.
TIDAL PRISM IN TIDAL SLOUGHS
AT NEWARK SLOUGH (AUDUBON MARSH)

FIGURE
5.2-8



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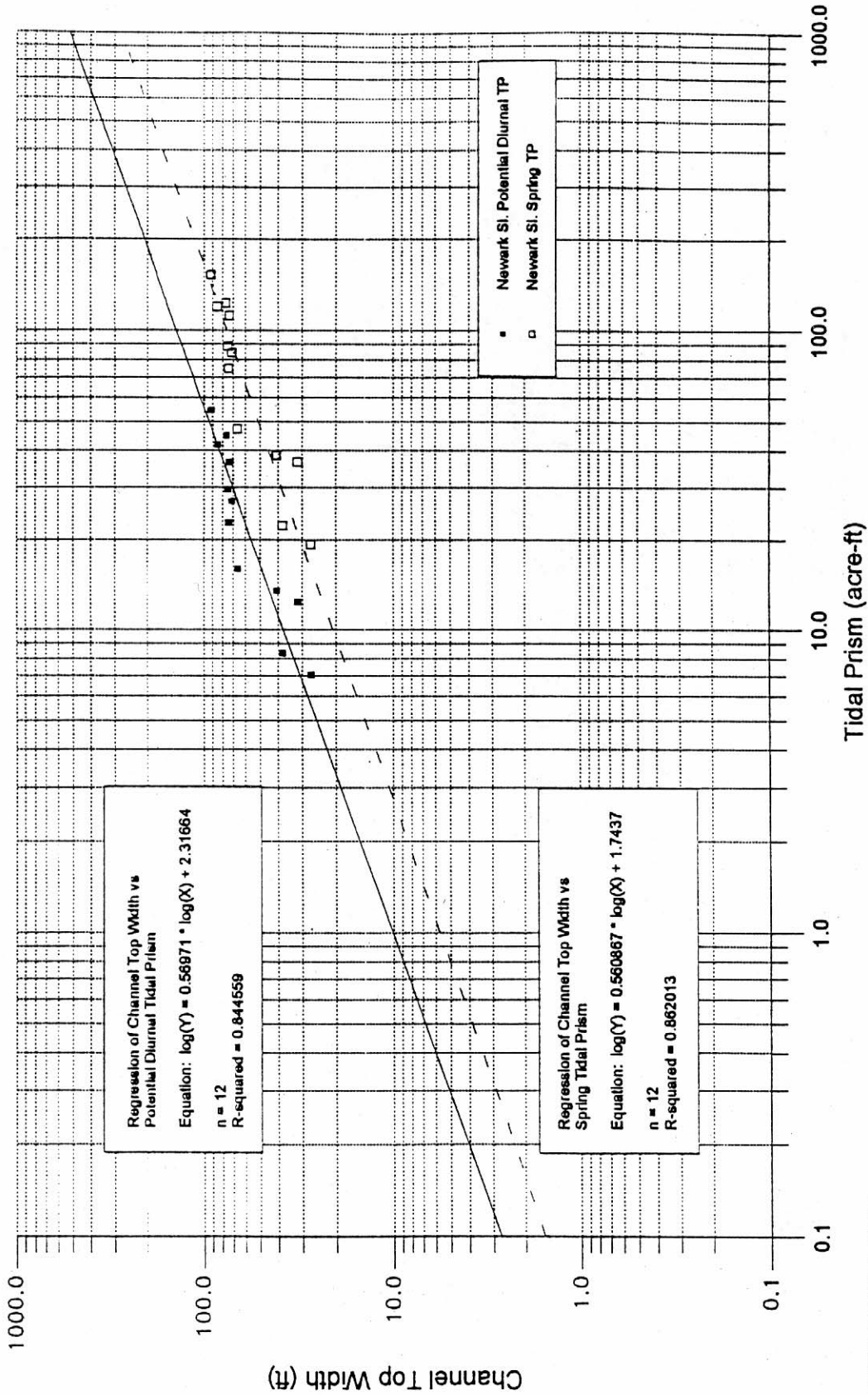


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CHANNEL CROSS-SECTIONAL AREA VS.
TIDAL PRISM IN TIDAL SLOUGHS
AT NEWARK SLOUGH (AUDUBON MARSH)



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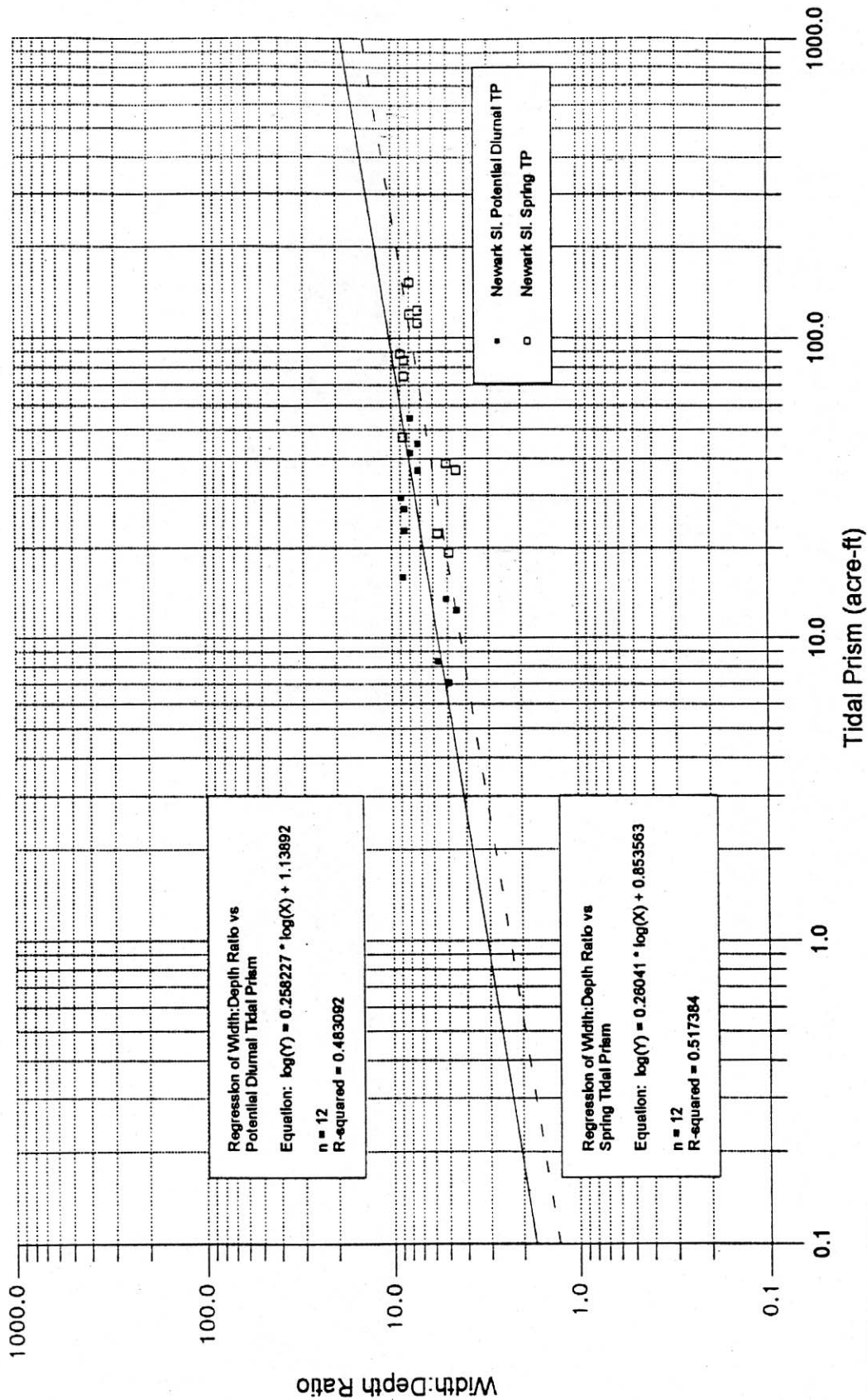


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CHANNEL TOP WIDTH VS.
TIDAL PRISM IN TIDAL SLOUGHS
AT NEWARK SLOUGH (AUDUBON MARSH)



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**WIDTH:DEPTH RATIO VS.
TIDAL PRISM IN TIDAL SLOUGHS
AT NEWARK SLOUGH (AUDUBON MARSH)**

**FIGURE
5.2-11**

6. SHAPE OF CHANNEL CROSS SECTIONS

In designing tidal channels, the shape of the cross section is probably not as important as the maximum depth and cross sectional area, since the shape is likely to change after construction due to scour and deposition of sediment. Nevertheless, some initial cross section shape must be specified in the design.

The cross sectional shape of tidal marsh channels depends on

- 1) the physical properties of the marsh sediments and plant roots;
- 2) the hydraulic effects of tidal flow in the channels.

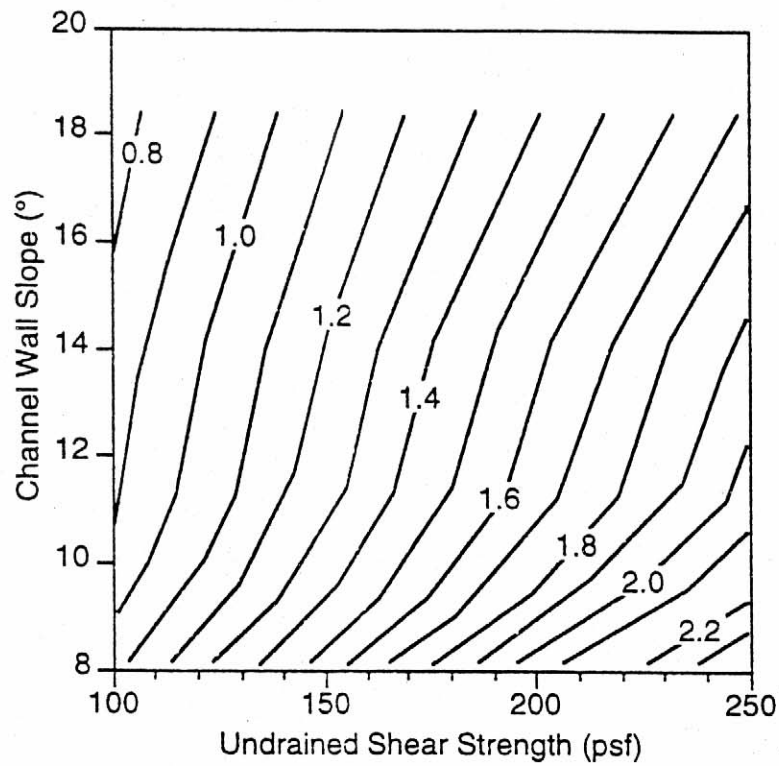
The problem of determining the equilibrium side slopes of a channel can be approached theoretically or empirically. A simple slope stability analysis can be used to calculate the equilibrium side slope in cohesive materials of different strengths. Appendix II describes such a calculation for typical tidal marsh sediments in San Francisco Bay, without vegetation. The equilibrium side slope is strongly dependent on the undrained shear strength of the sediment. Very soft bay mud with a shear strength of 100 lbs/ft² will only be stable at a gradient near 7:1. Well-consolidated bay mud with a strength of 150 lbs/ft² will support a bank 10 ft high with a slope of 3:1. Figure 6-1 shows lines of equal factor of safety for slopes in bay mud, for varying undrained shear strength and channel wall slope.

In a more empirical approach, channel side slopes can either be measured directly, or calculated from other cross section variables (width, depth and area). In making direct measurements, some assumptions about channel shape are necessary. Field surveys of channels often identify three slope segments or facets: 1) an upper slope, transitional from the channel side wall to the bank; 2) the channel wall; and 3) the toe facet, at the base of the channel wall. Using a set of cross sections from a marsh in north San Francisco Bay, the side slopes were broken up into three facets, and averages calculated for each facet, and for the side slopes as a whole. Figure 6-2 shows an idealized subdivided cross section, the marsh plain sloping away from the top of bank (due to natural bank-top levees). Table 6-1 shows the results, which are consistent with the calculations described in Appendix II.

Channels can also be assumed to be trapezoidal, parabolic or V-shaped. Everts (1980) treated channels as either parabolic or V-shaped. Channels which carry less than 600 m³ on the ebb cycle were found to be generally V-shaped; those with a tidal prism greater than 1400 m³ were found to be parabolic in shape. Most design problems deal with 3rd to 5th order channels, where the parabolic assumption is applicable. The parabolic assumption was used above, in order to derive a relationship for channel width that is consistent with the definitions of depth and cross sectional area. If a trapezoidal shape with given side slopes is assumed and depth and cross sectional area taken from the tidal prism relationships, then the top

TABLE 6-1
CHANNEL SIDE SLOPES AT MUZZI MARSH

	Channel Facet			
	Bank	Wall	Footslope	Overall
Average Slope	0.135	0.348	0.075	0.156
Standard Deviation	0.079	0.184	0.048	0.094
<i>n</i>	47	53	51	59



Lines of equal factor of safety for slopes underlain by Bay mud are shown relative to tidal marsh channel wall slope and Bay mud strength.

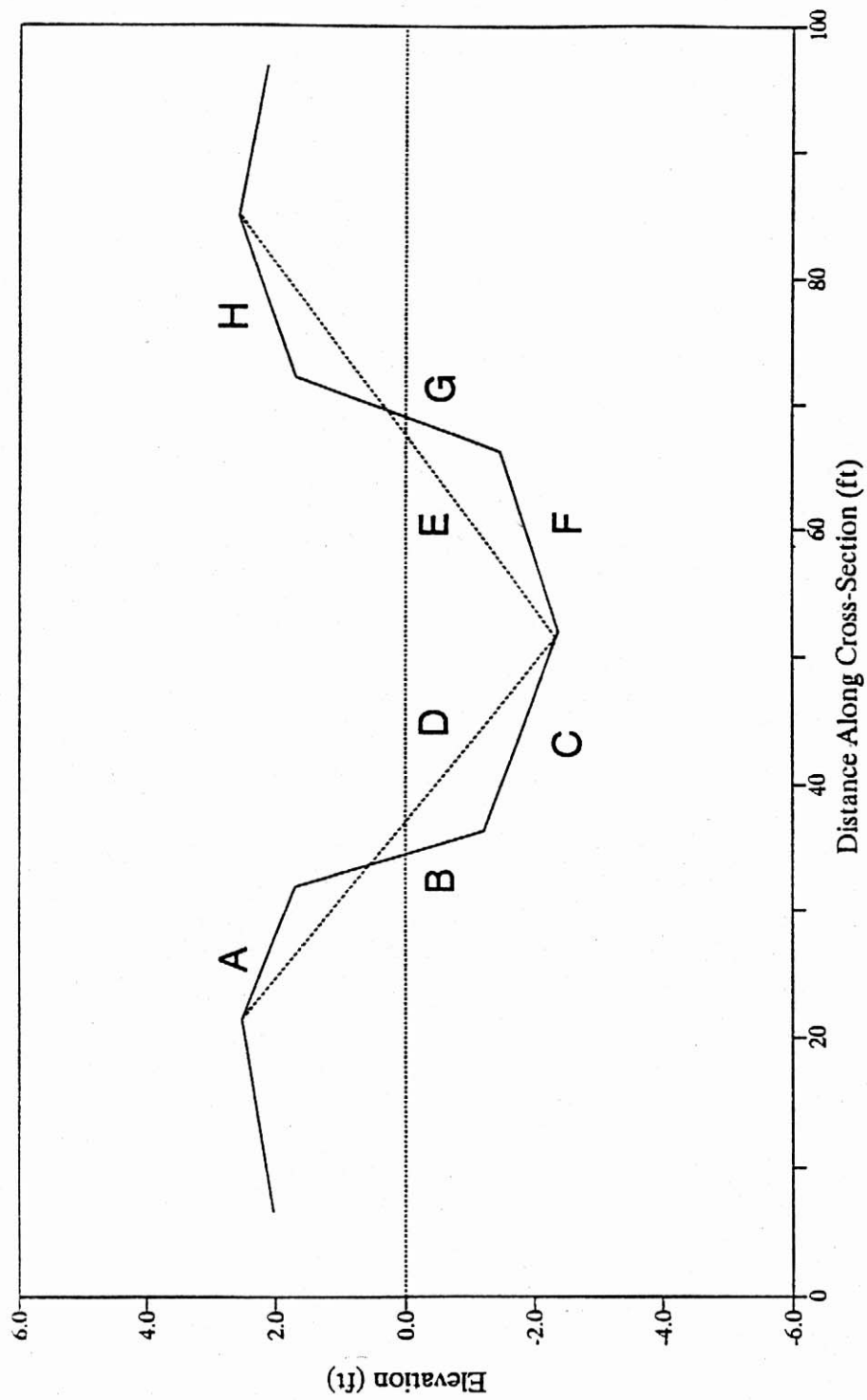
Source: William Lettis & Associates, Inc.



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Lines of Equal Factor of Safety for Slopes

Figure
6-1



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IDEALIZED CHANNEL CROSS-SECTION SHOWING CHANNEL SIDE SLOPE PARAMETERS

Figure
6-2

and bottom widths are defined. If a parabolic shape is assumed, then the top width can be calculated from area and depth, or taken off Figure 5.2-6.

As a practical matter, however, a parabolic cross section is almost impossible to construct by excavation, especially since plant roots may play a role in supporting the steep upper banks, and plants may be absent from the site. A reasonable compromise is to construct a trapezoidal or V-shaped channel with side slopes of 3:1 to 6:1. Natural channel scour and sediment deposition will soon adjust the channel side slopes to some new equilibrium, and the equilibrium side slope will increase as vegetation becomes established.

7. THE PLAN VIEW OF CHANNELS

The plan view features, or morphometry, of tidal marshes can be quantitatively discussed by describing such characteristics as channel length, sinuosity, placement within the drainage network (or channel order), and density of channels within the marsh area (or drainage density). Many of the techniques used to describe marsh morphometry have been borrowed or modified from fluvial geomorphology. These methods, developed by Horton (1945), Strahler (1964), Schumm (1956), and others, allow quantitative geomorphic analysis of similar features within a wide range of environments. Empirical morphometric data collected within both Southern California marshes and San Francisco Bay marshes is displayed in Tables 7-1 through 7-3. Tables 7-1 and 7-2 show morphometric parameters for a variety of marsh types, and include data recently collected from both naturally existing marshes and restored marshes, as well as data collected from a historic map of a naturally existing marsh. Table 7-3 shows empirical data collected by Pestrong (1965) from naturally existing marshes in southern San Francisco Bay. Figure 7-1 shows the location of each marsh for which data has been collected. Descriptions of method, applicability and analysis of each morphometric technique is discussed below.

Given adequate maps or aerial photographs, drainage networks can be broken down into individual channel segments, defined hierarchically by channel order, counted and measured. The problem arises, however, that visibility and recognition of the smallest stream order depends on the scale and accuracy of the media being used, whether a low altitude aerial photograph or topographic map. This problem was first observed by Leopold and Miller (1956) and further discussed by Florsheim and Williams (1994), who recommend that consistent scale be used between sites, and that detailed topographic media (such as 1:3,000 color infra red photogrametry) be used and field documented to verify that the entire slough channel network is mapped. Table 7-4 shows the scale of the topographic media from which empirical morphometric data in Tables 7-1 and 7-2 were collected. Because scales differ between 1:1,200 (1"=100 ft) and 1:10,000 (1"=833 ft), strict evaluation of the data is not recommended; however, the data do suggest approximate ranges for the morphometric parameters most useful in engineering channel design and drainage networks.

7.1 CHANNEL ORDER

Horton (1945) proposed a hierarchical system of ordering channel segments as a means of comparing channels of different size within and between drainage networks. This method was further modified by Strahler (1964), and has been applied to tidal channel networks. Hierarchical order begins with the smallest of channel segments and increases in order when two channels of same order connect. Thus, the smallest, singular channels in the system are considered to be first order. When two first order channels join, the subsequent portion of the channel is considered to be second order. A third order channel forms when two second order channels join, and so on. A low order channel, such as a first order channel,

TABLE 7-1
MORPHOMETRIC CHARACTERISTICS OF VARIOUS SOUTHERN CALIFORNIA MARSHES

LOCATION	CHIEK ORDER	NUMBER OF CHANNELS	SINUOUS LENGTH (ft)	STRAIGHT LENGTH (ft)	AVERAGE LENGTH (ft)	TOTAL LENGTH (ft)	TOTAL AREA (ACRES)	DRAINAGE DENSITY	LENGTH RATIO	AVERAGE SINUOSITY	BIFURCATION RATIO
E. Street Marsh - North Drainage	1st	22	2283	1403	104	5810	11.4	0.012	0.34	1.36	3.67
	2nd	6	1843	856	307				0.71	1.82	6
	3rd	2	861	497	431				0.52	1.74	2
	4th	1	823	515	823					1.6	
E. Street Marsh - South Drainage	1st	9	594	455	66	2920	6.4	0.011	0.1	1.13	3
	2nd	3	1888	931	629				1.44	1.92	3
	3rd	1	438	348	438					1.25	
F. & G. Street Marsh	1st	10	1022	689	102	2983	5.51	0.012	0.23	1.52	3.33
	2nd	3	1307	600	436				0.67	1.72	3
	3rd	1	654	346	654					1.89	
Sweetwater Marsh - Drainage M	1st	7	819	723	117	1910	6.34	0.007	0.29	1.1	3.5
	2nd	2	794	599	397				1.34	1.28	2
	3rd	1	287	283	297					1.05	
Sweetwater Marsh - Drainage N	1st	10	1353	1028	135	2041	4.51	0.01	1.05	1.27	3.33
	2nd	3	388	290	129				0.43	1.21	3
	3rd	1	300	280	300					1.07	

TABLE 7-2
MORPHOMETRIC CHARACTERISTICS OF VARIOUS SAN FRANCISCO BAY MARSHES

LOCATION	CREEK ORDER	NUMBER OF CHANNELS	SINUOUS LENGTH (ft)	STRAIGHT LENGTH (ft)	AVERAGE LENGTH (ft)	TOTAL LENGTH (ft)	TOTAL AREA (ACRES)	DRAINAGE DENSITY	LENGTH RATIO	AVERAGE SINUOSITY	BIFURCATION RATIO
Audubon Marsh (Newark Slough)	1st	120	18357	12673	153	37258	84.3	0.01	0.57	1.35	3.87
	2nd	31	8316	5650	268				0.49	1.39	2.82
	3rd	11	6009	4357	546				0.84	1.38	5.5
	4th	2	1301	978	651				0.2	1.23	2
	5th	1	3275	1793	3275					1.83	
San Francisco (S. S.F. Bay Historic Marsh)	1st	800*	169,280*	109,920*	212*	293893	976	0.007	0.63	1.45	4.82
	2nd	166	55589	33664	335				0.49	1.57	4.05
	3rd	41	28069	16128	685				0.33	1.67	3.73
	4th	11	22934	15726	2085				0.57	1.38	3.67
	5th	3	11021	5163	3674				0.52	2.1	3
	6th	1	7000	4260	7000					1.64	
Laumeister Tract	1st	57	9347	164	164	21733	83.4	0.006**	0.36	1.21**	3.35
	2nd	17	7821	460	460				0.46		5.67
	3rd	3	2973	991	991				0.62		3
	4th	1	1592	1592							
Faber Tract (Restored Marsh)	1st	115	7927	69	69	19049	81.3	0.005**	0.11	1.10**	9.58
	2nd	12	7347	612	612				1.03		3
	3rd	4	2370	593	593				0.74		2
	4th	2	1605	803	803						
Muzzi Marsh (Restored Marsh)	1st	92	8845	96	96	20640	51.2	0.009**	0.34	1.51**	4.38
	2nd	21	5915	282	282				0.38		4.2
	3rd	5	3666	733	733				0.66		2.5
	4th	2	2214	1107	1107						
Corte Madera Ecological Reserve	1st	186	17669	95	95	34470	77.8	0.010**	0.38	1.11**	4.65
	2nd	40	10115	253	253				0.75		2.86
	3rd	14	4719	337	337				0.68		3.5
	4th	4	1967	492	492						

* Number of first order channels inferred due to scale of topographic media.
** Sinuosity and Drainage Density measured for a selected slough system within marsh.

TABLE 7-3

MORPHOMETRIC CHARACTERISTICS OF SOUTHERN SAN FRANCISCO BAY MARSHES (MODIFIED FROM PESTRONG, 1965)

LOCATION	CRUEK ORDER	NUMBER OF CHANNELS	AVG. SINOUS LENGTH (FT)	AVG. STRAIGHT LENGTH (FT)	TOTAL LENGTH (FT)	TOTAL AREA (ACRES)	DRAINAGE DENSITY	LENGTH RATIO	AVERAGE SINOUSITY	BIFURCATION RATIO
PG&E	1st	142	27	24.4	12672	6.4	0.045	0.3	1.11	4.3
	2nd	33	88.6	63.9				0.69	1.39	3.3
	3rd	10	128.9	89.3				0.08	1.41	10
	4th	1	1685	974					1.73	
Dunbarton Point (DBR)	1st	57	49.2	38.4	7392	5.76	0.029	0.45	1.28	3
	2nd	19	109.4	75.8				0.2	1.44	4.8
	3rd	4	535.8	265.8				1.65	2.02	4
	4th	1	324	300					1.2	
Cooley Landing (CLY)	1st	92	46.4	35.2	8976	5.76	0.035	0.54	1.32	3.3
	2nd	28	85.7	57.5				0.5	1.49	5.6
	3rd	5	170	106				0.23	1.6	2.5
	4th	2	755	375				4.72	2.01	2
	5th	1	160	145					1.1	
Dunbarton Bridge (DBR)	1st	152	42.1	33.4	14256	10.24	0.032	0.49	1.26	3.3
	2nd	46	85.7	63.2				0.41	1.36	3.8
	3rd	12	210.3	144.3				0.66	1.46	4
	4th	3	319.7	190.7				0.51	1.62	3
	5th	1	633	594					1.07	
Redwood City Yacht Harbor - A	1st	169	57.2	46.9	25344	37.12	0.016	0.45	1.22	3.8
	2nd	44	128.3	94.7				0.2	1.36	5.5
	3rd	8	627.8	248				0.52	2.52	2
	4th	4	1203	787				2.49	1.53	4
	5th	1	484	372					1.3	
Redwood City Yacht Harbor - B	1st	55	44	38.4	4910	7.04	0.016	0.62	1.15	4.6
	2nd	12	71.3	55.8				0.6	1.28	3
	3rd	4	118	93				0.1	1.27	4
	4th	1	1165	695					1.67	
Redwood City Yacht Harbor - C	1st	195	54.8	43.9	24816	44.8	0.013	0.48	1.25	4
	2nd	49	115.1	80.9				0.33	1.43	3.5
	3rd	14	345.2	195.6				0.43	1.77	4.7
	4th	3	769.3	595				1.39	1.34	3
	5th	1	1103	670					1.65	

joining a higher order channel does not alter the order of the latter. The highest order found in a drainage system is used to define the order of that system. Figure 7.1-1 (B) shows an example of stream order within a tidal marsh drainage system.

Horton (1945) found that fluvial stream order is related to numbers of channel segments, channel segment length and drainage basin area by simple geometric relationships. When plotted on semi-log paper, these data plot as a straight line. Pestrone (1965) showed how estuarine systems followed the trend of perennial and ephemeral fluvial systems. Data collected more recently from both Southern California and San Francisco Bay are plotted in Figures 7.1-2 through 7.1-4, and follow the same trend.

7.2 CHANNEL BIFURCATION

As in fluvial systems, tidal drainage systems develop by repeated division of single channel segments into two branches. This process is called bifurcation, and where two channels separate the channel is said to bifurcate. The bifurcation ratio (R_b) is the ratio of the number of channels in a given channel order (N_o) to those of the next highest order (N_{o+1}):

$$R_b = \frac{N_o}{N_{o+1}}$$

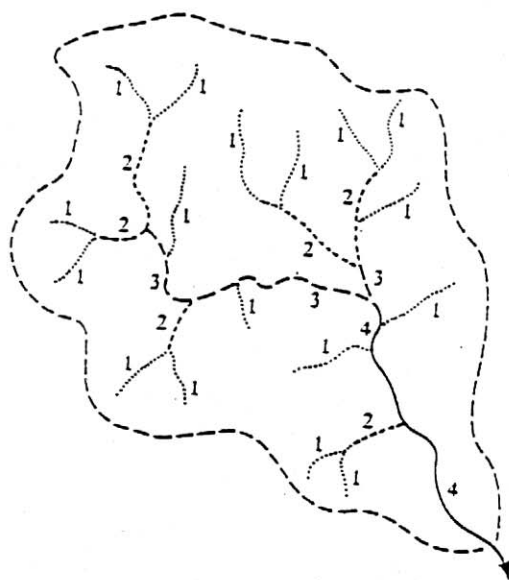
Evaluation of the bifurcation ratio allows for rapid estimates of the number of channels in any given order, as well as the total number of channels in a marsh (Florsheim and Williams, 1994). Leopold *et al.* (1964) found that for terrestrial stream networks, the bifurcation ratio tends toward 3.5. Data collected from tidal marshes show similar bifurcation ratios (Tables 7-1 through 7-3) which average to 3.5. It is recommended that the 3.5 bifurcation ratio, found in both fluvial and natural tidal marsh drainage networks, be used as a general guideline in designing channel drainage networks.

7.3 CHANNEL LENGTH

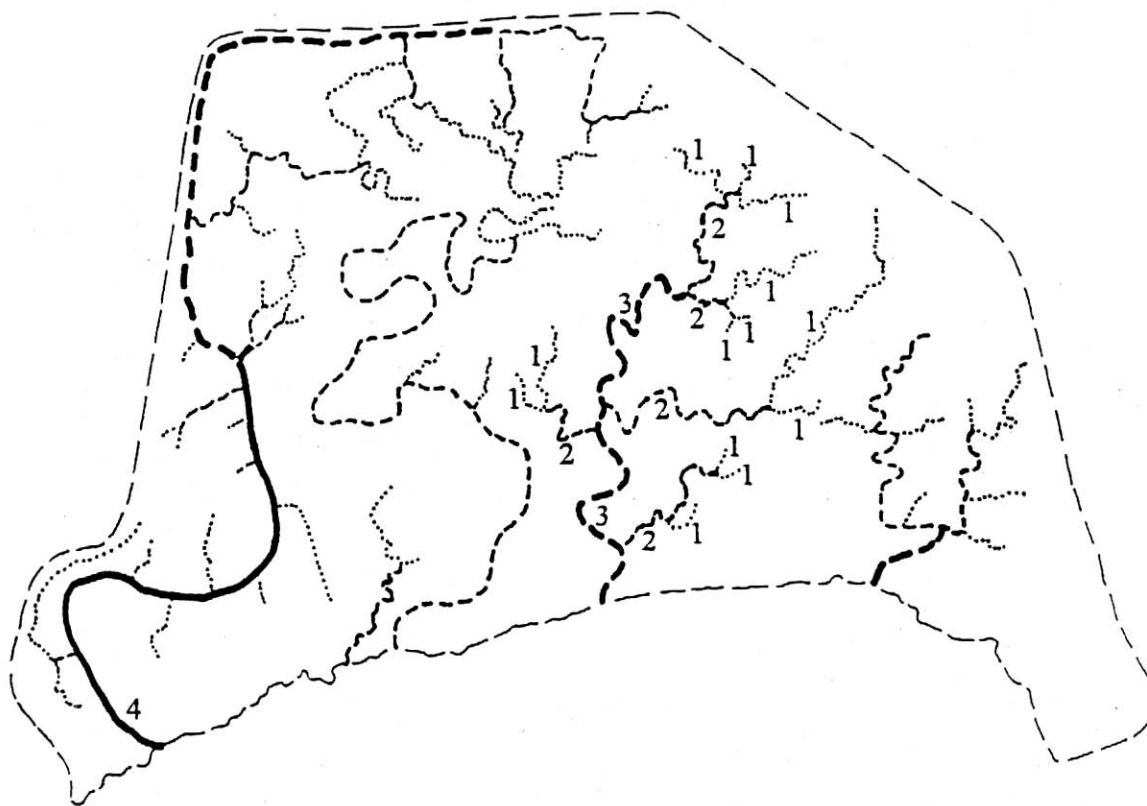
Evaluation of the channel lengths by order (Tables 7-1 through 7-3, and Figure 7.1-3) shows that the average length of first order channel segments are generally the lowest and that average channel length increases as channel order increases, as recognized previously by Horton (1945) and Pestrone (1965). For engineering and designing tidal channels, the length parameters most useful to evaluate are length ratio and channel order distribution.

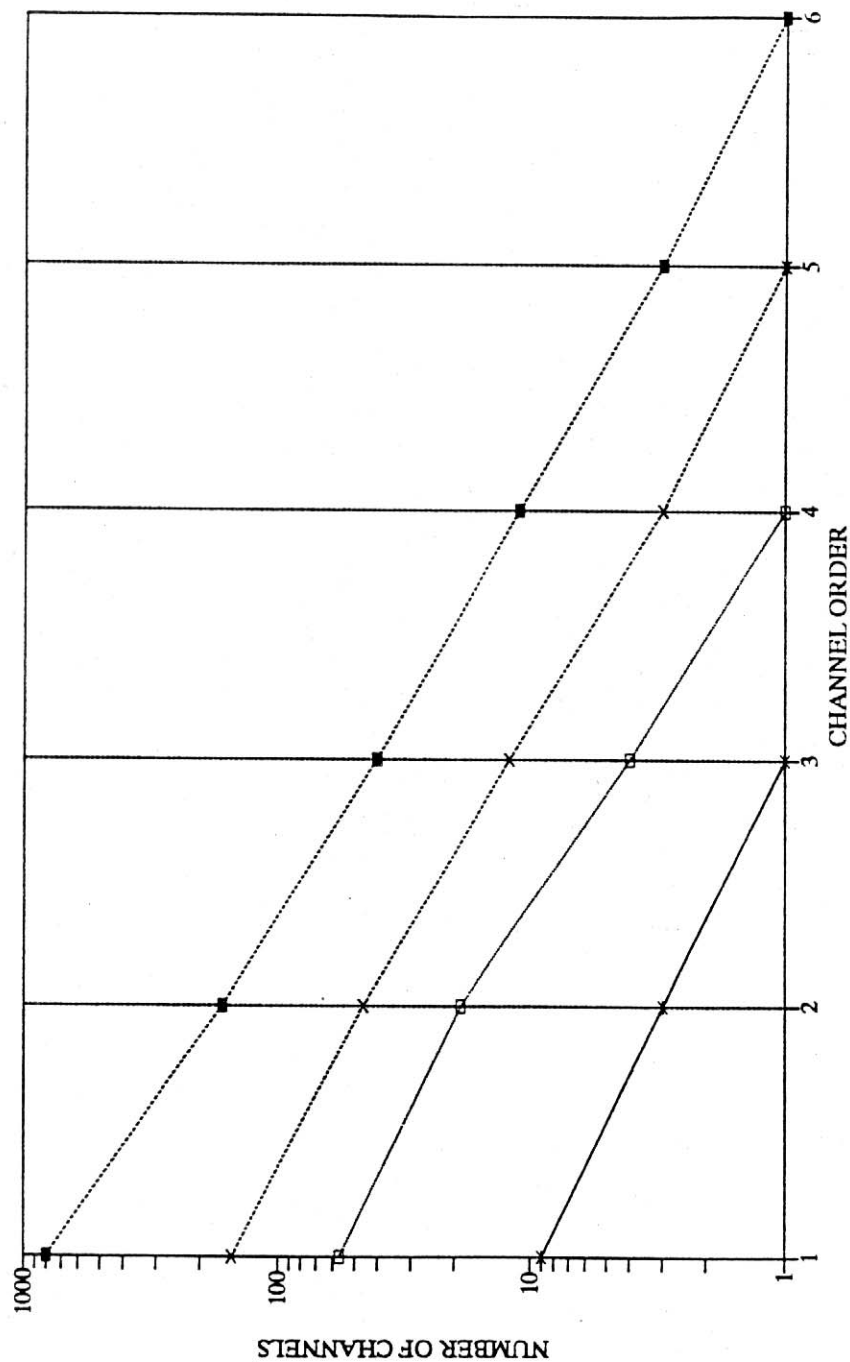
The length ratio (R_L) is the ratio of the average length of streams in a given order (L_o) to the average length in the next highest order (L_{o+1}):

(A) Stream ordering by the rules proposed by Strahler (1964).



(B) Strahler's (1964) ordering system applied to tidal sloughs (Laumeister Tract).





*- 3RD ORDER SYSTEM □- 4TH ORDER SYSTEM ·- 5TH ORDER SYSTEM ■- 6TH ORDER SYSTEM

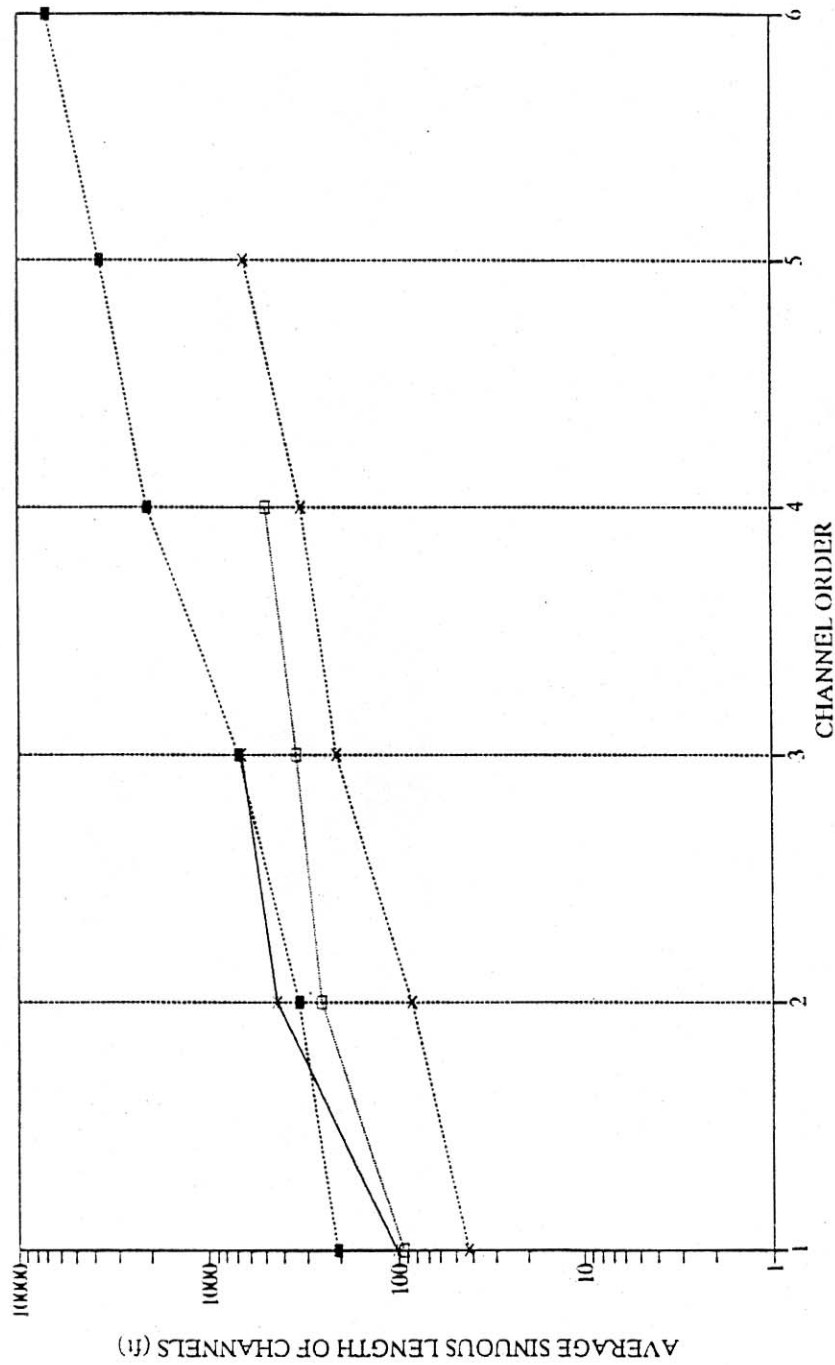
CKC034CHNL MORPHOM. WQI NUMBER VS ORDER 8-22-94



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NUMBER OF TIDAL CHANNELS VS CHANNEL ORDER FOR EACH DRAINAGE SYSTEM ORDER

Figure
7.1-2



✕ 3RD ORDER SYSTEM □ 4TH ORDER SYSTEM ✕ 5TH ORDER SYSTEM ■ 6TH ORDER SYSTEM

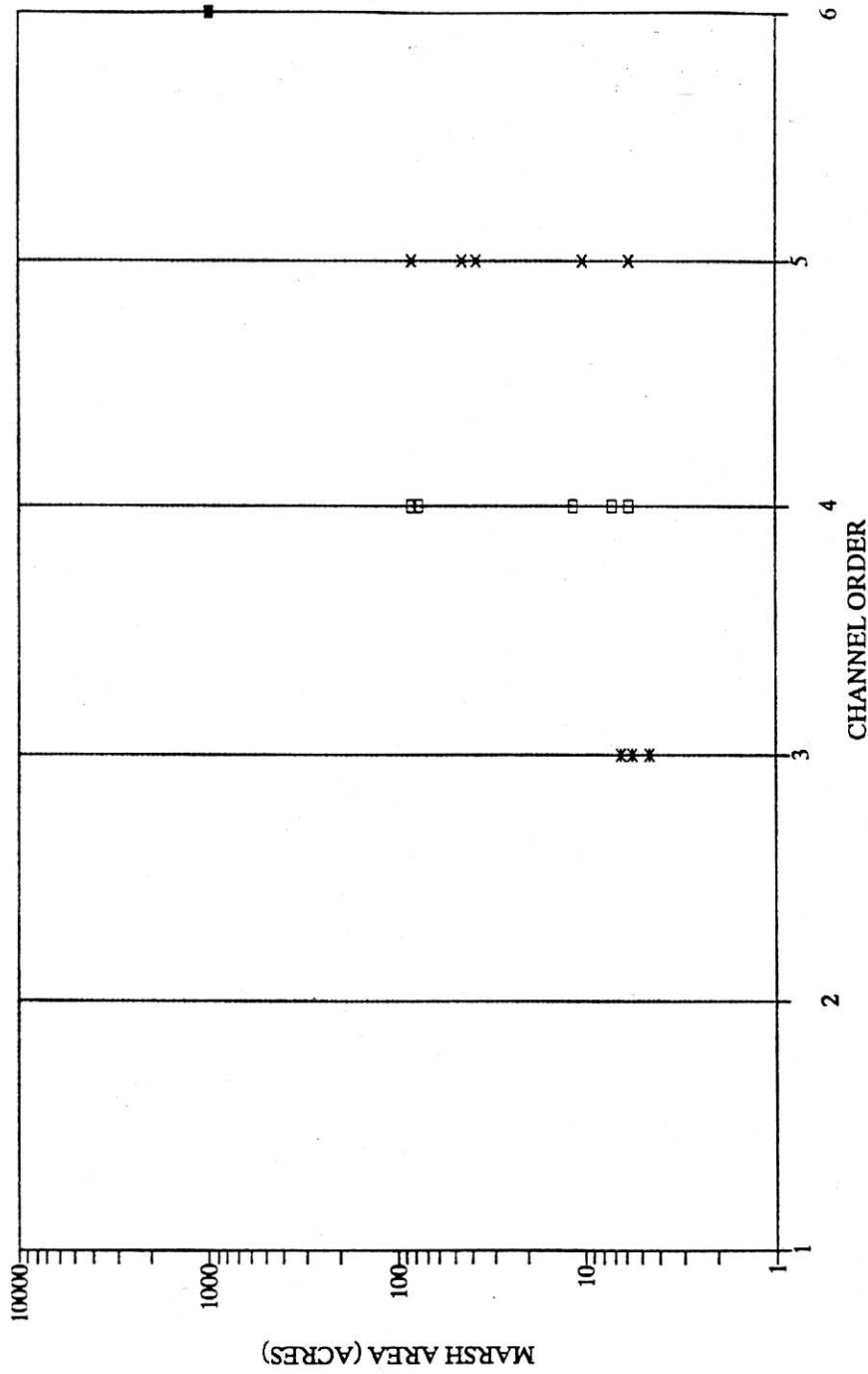
CKC934C1N1.MORPHOM.WQ1A.VGSINLENGTH.M-23-95



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AVERAGE LENGTH OF CHANNEL VS CHANNEL ORDER
FOR EACH DRAINAGE SYSTEM ORDER

Figure
7.1-3



CKC934-CHNL.MORPHOM.WQ1A.VOSINLENGTH18-22-94



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**MARSH AREA VS CHANNEL ORDER
FOR EACH DRAINAGE SYSTEM ORDER**

**Figure
7.1-4**

$$R_L = \frac{L_0}{L_{0+1}}$$

Evaluation of the length ratio provides a qualitative assessment of the relative lengths of tidal channels in different orders (Florsheim and Williams, 1994). Hence, channel networks can be developed such that length ratio relationships be followed (Table 7-5). Although empirical data displayed in Table 7-1 and 7-2 differs to some degree, they can be used as general indicators of the relative lengths of tidal channels found in tidal marshes of different order. Since most design problems deal with third to fifth order systems, consistency between these systems is of more concern to us than is variation between lesser ordered systems. Table 7-5 shows the relative length ratios for third, fourth and fifth order systems. The greatest variation in length ratios is observed within third order systems. Refinement of length ratio parameters for third order systems may come from further research, but in the absence of such efforts, it is recommended that other third order systems local to the project area be evaluated prior to design.

Channel distribution (C) can be determined for each order by multiplying the average channel length in ft (L_{avg}) by the number of channels in that order (n_o) and dividing by the total length in ft of channels within the marsh (L_T).

$$C = \frac{L_{avg} \times n_o}{L_T}$$

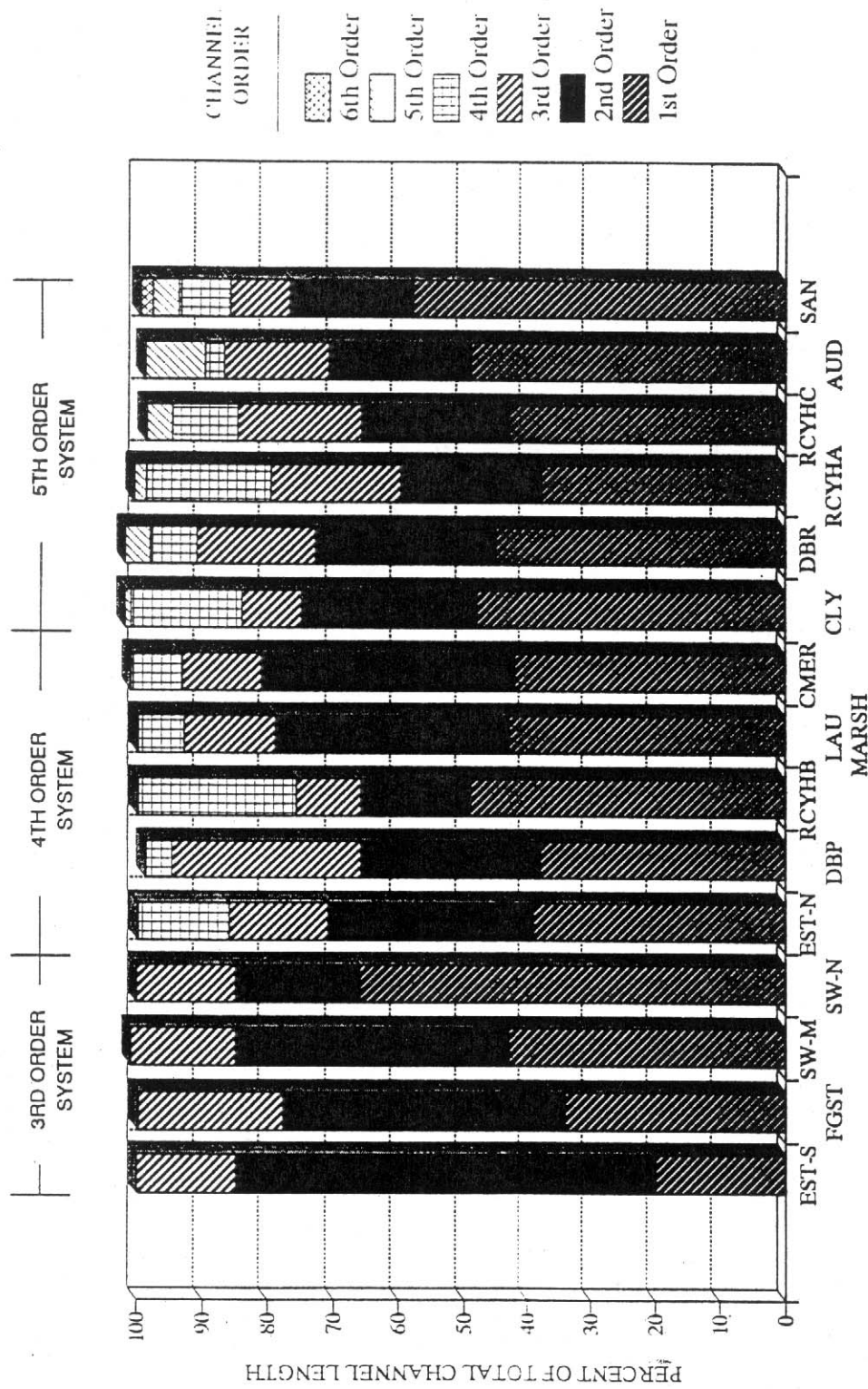
Thus for each order system, a particular channel distribution is found to occur. Figure 7.3-1 displays the percent distribution by channel order for each marsh within our data set. Marsh systems have been grouped by drainage system order. Although a range in channel distribution within third, fourth and fifth order systems exists due to the natural variability between marshes, these channel distribution values may be useful as a general guideline in designing drainage systems and channel networks. Table 7-6 shows the distribution of channels by drainage system order found to occur within the marshes used in this study.

7.4 CHANNEL SINUOSITY

Channel sinuosity (s) is defined as the ratio of sinuous length of the channel segment (L_{sin}) to the straight

$$s = \frac{L_{sin}}{L_{str}}$$

line length of the channel segment (L_{str}):



CKC934-CHNL.MORPHOM.WQ1.DISTRIBORDER.8-22-94



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CHANNEL DISTRIBUTION -
PERCENT OF CHANNEL LENGTH BY ORDER

Figure
7.3-1

Leopold *et al.* (1964) used sinuosity ratios to distinguish between braided, straight and meandering rivers. In their system, sinuosity values of 1.5 or greater are termed meandering, while values of 1.5 or less are termed sinuous or straight (obviously, the closer the sinuosity ratio tends to unity, the straighter the channel). Average sinuosity ratios calculated from numerous measurements of California marshes show a range of between 1.1 and 2.0 (Tables 7-1 through 7-3). The sinuosity for tidal marsh channels generally increases with increasing order (Pestrong, 1965). It has been noted that since the highest order channel in a drainage system often extends out across the adjacent mudflat, measurement of the highest order channel within the marsh plain itself leads to anomalously low sinuosity values for that channel order. This may well explain why sinuosity ratios generally increase with increasing order up to one order less than the system order, and then appear to decrease for the last, highest channel order (Tables 7-1 through 7-3).

The sinuosity of a particular drainage network (P) can also be defined by using the ratio of the inuous channel length of the main tidal channel (L_c) to the straight line length of the channel's drainage system (L_d):

$$P = \frac{L_c}{L_d}$$

In tidal marsh systems, channel sinuosity is indicative of slough channel development. Florsheim and Williams (1994) show that for selected slough drainage systems, sinuosity is greater within naturally existing marshes than within restored marshes (see Table 7-2: Laumeister vs Faber Tract, and Corte Madera Ecological Reserve vs Muzzi Marsh). They note that the lower sinuosity of restored marshes may be related to differences in the relative height of marsh plain elevation, tidal characteristics and vegetation differences versus those of naturally existing marshes.

7.5 DRAINAGE DENSITY

Drainage density (D) is used as a measure of the abundance of slough channels and is defined as the length of all channels in a marsh (L_T) divided by the marsh area (A):

$$D = \frac{L_T}{A}$$

In tidal marshes, a high drainage density is associated with frequency and sinuosity of tidal channels, both of which are characteristic of good tidal circulation (Florsheim and Williams, 1994). As discussed previously, the scale of the topographic media from which such data is collected can strongly influence the results of this calculation, so efforts should always be made to use materials which have the greatest amount of detail and accuracy, with as little variation in scale as possible. Since field checking of the

topographic media used in the morphometric analyses could not be undertaken (and was impossible to do in the case of historic maps), one should use these values as general guidelines rather than as definitive values. Drainage densities calculated from data collected at numerous California marshes (Tables 7-1 through 7-3) tend to equal 0.01 to 0.02 ft/ft². Hence, the common drainage system contains 435.6 to 871.2 ft of channel for every acre of marsh. Variation in drainage density values differ between 0.005 and 0.045. It is thought that variation is due to age and hence maturity of marsh, with older marshes showing greater drainage densities than younger marshes (Florsheim and Williams, 1994).

7.6 USE OF MORPHOMETRIC CRITERION IN TIDAL CHANNEL DESIGN

The success of a marsh creation, restoration or enhancement project depends on the ability of the designed system to function as effectively as a natural system, under a particular tidal range and regime. Evaluation of plan view features, or morphometry show that general trends exist within a particular marsh as well as among marshes of different size and drainage system order. The use of general guidelines developed from such trends can help designers and engineers design tidal wetland creation, restoration or enhancement projects which more closely approximate natural systems, and so increase the potential for the success of the project. The following morphometric guidelines can be used in tidal wetland creation, restoration and enhancement projects:

- Drainage density, it would seem, is the most important parameter of marsh morphometry, in that it provides the life-blood (so-to-speak) to the arterial network of the tidal marsh system. Drainage densities of 0.01 to 0.02 ft/ft² have been found to occur in a number of natural marshes and can be used as a general guideline in designing the total length of tidal channels per area of marsh planned. This drainage density value is equivalent to creating 435.6 to 871.2 ft of channel for every acre of marsh created, or existing.
- Bifurcation ratio of 3.5 can be used to determine the number of each channel order, as well as the total number of channels to design.
- Length ratios for a particular order drainage system should be used as general guidelines to determine the length of each channel order within the desired order drainage system (use Figure 7.3-1).
- The distribution of channels for a particular order drainage system can be obtained from Table 7-6 and used as a general guideline for further defining the number of channels in each order in a particular order drainage system.
- Tidal channel sinuosity of 1.1 to 2.0 can be used in the design of third to fifth order channels. Construction methods may constrain the ability to which channel sinuosity can be implemented. First order channels have the lowest sinuosity values and can either be

TABLE 7-4

**SCALE OF TOPOGRAPHIC MEDIA USED
FOR EMPIRICAL MORPHOMETRIC DATA COLLECTION**

Marsh	Topographic Media	Scale
E. Street Marsh - North Drainage	Detailed Contour Map	1 : 1,200 (1" = 100')
E. Street Marsh - South Drainage	Detailed Contour Map	1 : 1,200 (1" = 100')
F. & G. Street Marsh	Detailed Contour Map	1 : 1,200 (1" = 100')
Sweetwater Marsh - Drainage M	Detailed Contour Map	1 : 2,400 (1" = 200')
Sweetwater Marsh - Drainage N	Detailed Contour Map	1 : 2,400 (1" = 200')
Audubon Marsh (Newark Slough)	Detailed Contour Map	1 : 1,200 (1" = 100')
San Francisquito Marsh	Historic Topographic Map	1 : 10,000 (1" = 833')
Laumeister Marsh	Aerial Photograph	1 : 6,000 (1" = 500')
Faber Tract (Restored Marsh)	Aerial Photograph	1 : 6,000 (1" = 500')
Muzzi Marsh (Restored Marsh)	Aerial Photograph	1 : 6,000 (1" = 500')
Corte Madera Ecological Reserve	Aerial Photograph	1 : 6,000 (1" = 500')

TABLE 7-6

DISTRIBUTION OF CHANNELS BY DRAINAGE SYSTEM ORDER.

Channel Order	Percent of Total Channel Length		
	3rd Order System	4th Order System	5th Order System
1st Order	20% to 60%	0.43	0.45
2nd Order	60% to 20%	38% to 24%	20% to 27%
3rd Order	20%	16%	14% to 18%
4th Order		5% to 17%	6% to 16%
5th Order			2% to 8%

allowed to naturally develop over time, or dredged as short, straight line segments in existing low spots of the marsh to avoid ponding within inter-marsh basins.

8. THE ROLE OF ORGANISMS IN CHANNEL FORMATION

Channels in tidal marshes generally evolve from channels developed initially on an unvegetated mudflat. In a mature vegetated marsh, however, plants, and to a lesser extent animals, exert a profound effect on channel form and process.

Vegetation generally protects sediment on channel banks, as well as the marsh plain, from erosion. Vegetation acts in two ways: first, it affects the velocity profile on and near the bed, reducing the shear stress on recently deposited soft sediment. Second, plant roots contribute to the shear strength of marsh soils, increasing the equilibrium side slopes along channels.

Pethick *et al.* (1990) found that the effect of vegetation on the boundary shear layer is complex; under some circumstances, vegetation can actually retard the deposition and accretion of marsh sediment. The vegetation creates a two-stage velocity profile; in the upper part of this profile, velocities are in excess of critical values needed to keep sediment in suspension; in the lower part of the profile, velocities are greatly reduced. The authors suggested that vegetation increases the depth of the upper layer, and that the lower layer is effectively isolated from the upper layer, so that sediment deposition is reduced. This mechanism depends to some extent on the distance between clumps of vegetation.

In the saltmarshes of San Francisco Bay, mudflats and channel banks are colonized first by cordgrass (*Spartina foliosa*). This plant is an effective sediment trap, and the newly deposited sediments are generally very soft, weak and susceptible to erosion. As sediment accumulates and the duration of tidal inundation decreases, cordgrass is replaced by pickleweed (*Salicornia virginica*). This plant forms dense root systems, greatly increasing the resistance of the marsh soil to surface erosion and bank slumping; the shear strength of marsh soils dominated by pickleweed is two to three times that of soils dominated by cordgrass (Pestrong, 1965; Steers, 1977; Van Eerd, 1985). As a result, channel banks in a mature marsh may be vertical or even undercut. Channel bank erosion and channel migration occurs when the banks fail by slumping into the channel.

Garofalo (1980) found in a study of channel migration in New Jersey wetlands, that vegetation is the main factor controlling the rate of channel migration, and that saltmarsh vegetation is much more effective in reducing channel migration than freshwater marsh vegetation. Channel migration was found to result from large infrequent storm events rather than incremental erosion associated with daily tidal action.

Burrowing animals can also affect the shear strength of marsh sediments and thus affect the erosion and failure of channel banks. The burrowing isopod *Sphaeroma quoyanum* was introduced to San Francisco Bay between the 1850's and 1890's by ships from Australasia. It forms extensive networks of burrows in

marsh soils, making them more susceptible to erosion. It is thought to have had a major impact on the erosion of marsh margins around San Francisco Bay (Carlton, 1979).

Although organisms play an important role in the formation of channels in tidal marshes, they obviously cannot be used directly in design and construction. Their long-term effect has to be taken into account, however. In some cases, it may be necessary to plant the channel banks and marsh plain to get vegetation established rapidly. In other cases, natural invasion by plants is rapid, and so planting is a waste of time. In any case, the design engineer needs to be aware of 1) what species of plants are likely to occupy the channel banks, and 2) what the effect of plants on channel banks and slough morphology will be. The equilibrium slope of raw, unvegetated channel banks will in most cases be lower than the slope of vegetated banks. If the banks are constructed initially at an oversteepened slope, they will probably fail by slumping before plants become established.

9. APPLICATIONS OF THE DESIGN METHODOLOGY

9.1 DEVELOPING A LOCAL DATA BASE

The tidal prism relationships developed in this study are applicable in marshes where silt and clay predominate over sand, and where the diurnal range is 4.3-8.4 ft. Where possible, however, it is better to derive a local relationship to use as a basis for design, rather than relying on data developed in a different region. The following steps should be carried out to develop a local data base for design work:

1. *Adopt a clear definition of the tidal prism variable, and characterize the local tidal regime.* Tidal elevations must be referred to a datum (such as NGVD) that can be used in construction. The channel velocities associated with spring tides are probably more effective in channel formation than those associated with average tides, but the potential diurnal tidal prism is easier to define, and will give suitable results.
2. *Select a reference natural marsh for developing a data base.* Criteria for selecting a study area include accessibility, lack of artificial fill or subsidence, age of marsh, and geomorphic and vegetational similarity to the area where the results will be applied.
3. *Obtain topographic data.* This should include a detailed topographic map showing channel planform and marsh plain elevations. In the absence of such a map, good aerial photography can be supplemented with spot elevations surveyed on the ground. Channel cross sections can then be surveyed and plotted.
4. *For each cross section, calculate the upstream tidal prism, taking account of both channel volume and marsh plain volume.* If equipment and budget are available, the tidal prism can be measured directly at a cross section by measuring discharge over a tidal cycle and integrating over time. This provides a good check on volume calculations, but is laborious.
5. *Delineate the marsh area that contributes ebb flow at each of the surveyed cross sections, using the map or an aerial photograph.*
6. *Plot the relationships between tidal prism and marsh area, and cross sectional area, depth and width.*

9.2 EXAMPLE PROBLEMS

9.2.1 Calculate the Dimensions of a New Tidal Channel

Suppose you want to restore tidal action to an historic tidal marsh that has been diked for many years. The marsh has subsided from its original elevation to an average elevation +1.0 ft NGVD, and a new tidal marsh has formed between the diked area and the tidal source. Assume that the area for restoration is 40 acres, and the diurnal range is from -2.8 ft NGVD to +3.2 ft NGVD. Assume that the relationships shown in Section 5 are applicable to your problems.

Calculate:

- 1) the dimensions of a channel and levee breach needed to provide full tidal action to the restoration area; and
- 2) the ultimate channel dimensions after a mature tidal marsh has formed in the restored area.

Solution:

The Potential Diurnal Tidal Prism in the restored area will be the volume between +1.0 and +3.2 ft (the elevation of MHHW), or 88 acre ft. From Figure 5.2-3, the cross sectional area should be about 400 ft², and from Figure 5.2-2 the channel should have a depth of about 8.3 ft below the elevation of MHHW, or a bottom elevation of -5.1 ft NGVD.

If you assume a trapezoidal cross section with 4:1 (horizontal:vertical) side slopes, the bottom width will be 44.2 ft and the top width will be 110.6 ft. If you assume a parabolic cross section, the top width will be $1.5 (400)/8.3$ or 72.3 ft.

In a sediment-rich environment, however, the area reopened to tidal action will accumulate sediment (provided that wind-generated waves are not severe), and a vegetated tidal marsh will ultimately develop. From Figure 5.2-1, the tidal prism in a mature 40 acre marsh should be about 30 acre ft. Using Figures 5.2-2 and 5.2-3, you can determine that the channel should have a depth of about 6.8 ft below MHHW, and a cross sectional area of approximately 225 ft².

In cases where a substantial tidal prism volume is available to drive tidal action, it may not be necessary to construct a channel or levee breach to the maximum equilibrium dimensions, however. Tidal velocities may be sufficient to erode the bed and banks of a

pilot channel, and this may allow considerable savings in excavation costs. The feasibility of this approach will depend on the erodibility of marsh sediments and levee material. A one-dimensional tidal hydrodynamic model can be used in such cases to calculate the bed shear stress-duration relationship, and infer the likelihood of channel scour. Local experience and engineering judgement are at least as important as model results.

9.2.2 Determine the Planform Geometry of a Newly Created Tidal Marsh System

Suppose you are asked to develop a tidal drainage system for these same 40 acres. You can do so by using parameters of planform geometry from other tidal marshes within the region of your site. For example, to determine the order of the drainage system that could be accommodated by the marsh area given, you can observe what order systems other marsh areas support within your region. To know the total length of channels that should be constructed, you can look at drainage densities of other marsh systems within your region. And to know the number and the lengths of channels of each order that should be designed, you can use the bifurcation ratio and the channel distribution pattern displayed by similar systems.

The following shows an example of developing a tidal drainage system for the 40-acre marsh described above:

Determine:

- 1) The order of the drainage system that can be accommodated within the 40-acre restoration area.
- 2) The total channel length that can be accommodated within the 40-acre site.
- 3) The number of channels of each order that should be designed.
- 4) The length of each order channel.
- 5) An idealized drainage pattern based on hierarchical order.

Solution:

Because we are developing this marsh system in California, we will use the values for marsh area vs order, drainage density, and bifurcation ratio found from numerous marshes in California to design our marsh system. Figure 7.1-4 shows us the maximum order system supported by specific marsh area. In general, larger marsh areas support

higher order tidal drainage systems. From Figure 7.1-4, we determine that a 40-acre marsh area can support up to a 3rd or 4th order system. Actually, since third order systems usually exist on approximately 10 acres, we could expect to develop four third order systems at our 40-acre site. If we wish to design a fourth order system, the 40-acre site would likely only support one such system.

Drainage densities at numerous California marshes tend to equal 0.01 to 0.02 ft per square foot of marsh area. If we develop our marsh system conservatively (to keep our costs down, and allow for continued evolution of the site), a drainage density of 0.01 ft/ft² would yield 17,424 ft of total channel length. If we wish to develop four third-order systems (as opposed to one fourth order system), we could easily divide the total length equally between the four systems, giving each system a total length of 4,356 ft.

The bifurcation ratio can be used to tell us how many channels of each order we need to design in our system. A bifurcation ratio of 3.5 has been found in our region. Therefore, if we were designing four third order systems, we would need one 3rd order channel, four 2nd order channels (we rounded 3.5 up to 4), and twelve 1st order channels for each system. If we were planning our design to contain one fourth order system, we would need one 4th order channel, four 3rd order channels, twelve second order channels and forty-three first order channels.

Now, we know the total length of channels to be developed and how many channels of each order. We must next determine how this total channel length is distributed to each channel order. From Figure 7.3-1 we can see that in third order systems, third order channels generally account for about 20 percent of total channel length, second order channels account for 20 to 60 percent of total channel length and 1st order channels also account for 20 to 60 percent of total channel length. If we plan to allow the first order channels to develop on their own, and construct only channels with channel order greater than one, we could construct up to 80 percent of the tidal drainage system, allowing the other 20 percent to develop naturally as the system evolves and equilibrates with the tidal prism that services the marsh. Each third order system, then, having a total channel length of 4,356 ft, would have one 3rd order channel designed to be 871 ft long (20 percent of total channel length), and four second order channels designed to each be 653 ft long (60 percent of total channel length divided among four channels). Based on this same method, we would expect something like twelve first order channels each approximately 73 ft long to develop naturally within each third order system.

If we were to design this marsh with one fourth order system, using Figure 7.3-1 again, we would see that in fourth order systems fourth order channels generally account for about 10 percent of the total channel length, 3rd order channels generally account for about 20 percent of total channel length, second order channels generally account for 30

percent of total channel length, and first order channels generally account for about 40 percent of total channel length. Therefore, the fourth order system we design would be constructed having one fourth order channel 1,742 ft long, four 3rd order channels each 871 ft long, and twelve second order channels each 436 ft long. We would again expect something like forty-three 1st order channels each approximately 162 ft long to develop naturally.

Figure 9.2-1 shows a schematic of the idealized drainage patterns of both the third order and fourth order systems we have just developed.

It should be recognized that the use of planform analysis would be best applied by referencing local or regional, naturally existing marshes to determine the most accurate planform design relationships relevant to the study site. Naturally existing marshes display geomorphic features (i.e., planform and cross section geometry) as a result of the physical and biological processes acting upon them. Because the scale and intensity of each of these processes is dependant upon regional variables such as geography, geology and climate, evaluation and analysis of similar tidal drainage systems within the study or project region would provide the most accurate design criteria for restoration or enhancement projects within that region.

Values of drainage density, bifurcation ratio and channel distribution obtained from such analysis should consider that such measurements are taken from continually evolving systems. This analysis is used to develop an idealized template. The design team may wish to emulate this template to varying degrees of scale and complexity, depending upon project resources and limitations (e.g., time, expense and goals).

9.2.3 Using the Tidal Prism in a Marina to Maintain a Navigation Channel

Suppose you have been asked to review the design a 5-acre boat marina with an entrance into an existing tidal channel. The present bottom elevation of the channel is at MLLW, and the developer asserts that with the increased tidal prism, the channel will be self-maintaining at an elevation 3 ft below MLLW. Assume the diurnal tidal range is 6.0 ft.

Solution:

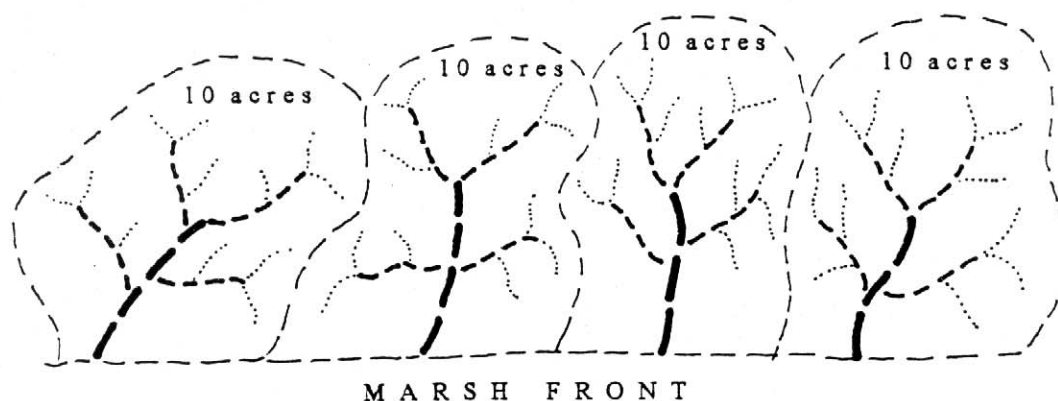
The existing channel depth is 6.0 ft below MHHW; the tidal prism required to maintain the channel is about 16 acre ft. The tidal prism needed to maintain a depth of 9 ft below MHHW is about 120 acre ft (from Figure 5.2-2). The marina would have to contribute 104 acre ft of tidal prism; with a diurnal range of 6.0 ft, the marina would have to have an area of over 17 acres. With only 5 acre of area, the tidal prism contributed by the marina would amount to 30 acre ft, and the total tidal prism in the channel would increase to about 46 acre ft, with an equilibrium depth of about 1.3 ft below MLLW.

(A) 40 Acre Marsh with Four 3rd Order Drainages

L E G E N D	
	3rd order channels
	2nd order channels
	1st order channels

For each 3rd order system:

- one 3rd order channel
- four 2nd order channels
- twelve 1st order channels

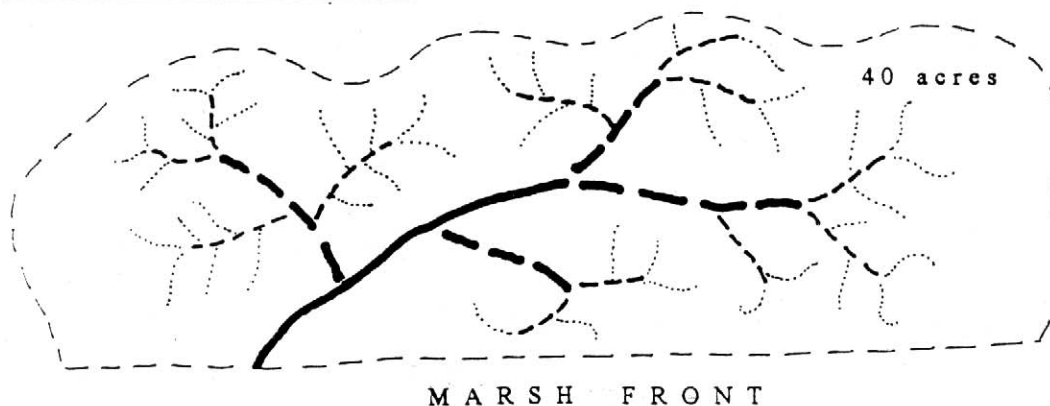


(B) 40 Acre Marsh with One 4th Order Drainage

L E G E N D	
	4th order channels
	3rd order channels
	2nd order channels
	1st order channels

For the 4th order system:

- one 4th order channel
- four 3rd order channels
- twelve 2nd order channels
- forty-three 1st order channels



10. USING NATURAL TIDAL ENERGY AND SEDIMENTATION TO CREATE SMALL CHANNELS

Using the methodology outlined above, the problem of designing and creating third order and larger slough channels is relatively straightforward. A natural tidal marsh, however, usually is characterized by a network of branching and sinuous small second and first order channels. Constructing such a channel network, especially in soft sediment, may present a formidable challenge. An alternative approach is to design and build the third-order and larger channels, and let natural sedimentation and erosion create the marsh plain with incised first and second-order channels. This approach is especially useful where dredged material is placed to create a base for a new tidal marsh. It can only work, however, in sediment-rich environments where rapid deposition of sediment occurs in quiet water.

Where dredged material is placed below the target marsh plain elevation (allowing for subsidence), sediment will begin to accumulate on the new surface, tidal action will create incipient small channels on the new artificial mudflat. The process can be seen in the development of natural tidal marshes. As the mudflat is invaded by plants and continues to increase in elevation, the incipient channels on the mudflat are maintained, and the marsh plain grows around them. It is possible that once tidal flow is confined to small channels, the channels may incise into the original surface of the dredged material.

Where dredged or other fill material is placed at an elevation appropriate for the final marsh plain, the tidal velocities and bed shear stress will be insufficient to create a new channel system. Where fill material is placed at too low an elevation, the invasion and growth of plants will be inhibited. Appendix III describes two tidal marshes in San Francisco Bay where dredged material was placed at too high an initial elevation, and a channel system never developed. In general, the finished elevation of dredged material or other fill material used to create a tidal marsh should be 1 to 1.5 ft below the elevation of MHHW.

11. RESEARCH NEEDS

This study has shown that the geometry of channels in tidal marshes can be related to the marsh tidal prism, and has developed local relationships for coastal marshes in California that can be used in slough channel design. Because of the similarity of geomorphic processes in different regions, it is hypothesized that the relationships can be applied in areas where the diurnal tidal range is between about 4.3 and 8.4 ft, and the sediments are primarily silt and clay. Additional studies, however, would help extend the method to other situations and other regions.

Useful additional studies include:

1. Collecting data in other regions with similar sediment composition and tidal regimes. These data would be useful for local design problems, and could be used to verify or nullify the hypothesis that the relationships developed in one region can be applied in other regions.
2. Collecting data in marshes with contrasting sediment composition, vegetation and tidal regime. This would help to elucidate the relative importance of these variables.
3. Examining how the physical variables of tidal flow in channels influence the channel geometry. This could be approached by measuring and modeling tide height and velocity over several tidal cycles in an undisturbed marsh.

12. SUMMARY AND CONCLUSIONS

1. *Tidal slough channels develop in response to inputs of tidal energy.* Although the specific conditions of tidal regime, sediment size and vegetation may vary from one marsh to another, the general processes and principles of channel formation and maintenance are similar throughout the world. For this reason, it is possible to develop empirical geomorphic relationships that can guide the design of tidal slough channels.
2. *Plants, animals, and microbes are all affected by tidal flows and their associated effects on substrate particle size and sediment chemistry.* Each species has specific requirements, many of which are not known. Tidal marshes are heterogeneous, and different types of channels support different organisms. Biological goals for channel design must be clearly defined. Both plants and animals play an important role in determining the morphology of slough channels.
3. *The hydraulic geometry of a channel can be described by empirical equations (in exponential or logarithmic form) that relate width, average depth, and velocity to discharge.* In rivers, discharge is an independent variable; in tidal channels it is a dependent variable.
4. *Tidal prism can be used as a surrogate for discharge, and empirical relationships developed between tidal prism and depth, width, cross sectional area and marsh area.* These relationships can be used to solve a number of design problems.
5. *Velocity pulses that occur during the ebb of tides that flood the marsh plain probably play a dominant roll in channel formation and maintenance.* For this reason, the spring tidal prism is probably the most appropriate for use as an independent variable. The diurnal tidal prism, however, is easier to define, and gives equally good results when plotted against depth, width, cross sectional area and marsh area.
6. *Tidal prism relationships developed for marshes in California should be applied with caution in other regions.* Where possible, local data should be collected and local relationships derived, using the methodology described in Section 9.1.
7. *Much uncertainty remains about the relationship between channel morphology and estuarine function.* Because of this uncertainty, channel and wetland design should aim at mimicking natural systems.

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Design Guidelines for Tidal Channels in Coastal Wetlands

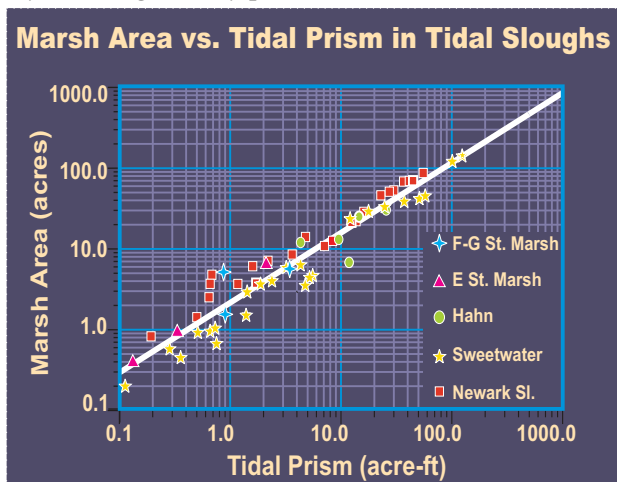


East side outfall channel

One of the most important design questions in tidal wetland restoration and in estuarine maintenance dredging projects has been the prediction of the size of equilibrium or self maintaining tidal channels. In 1981 PWA first developed a predictive tool based on empirical hydraulic geometry relationships derived from field measurements of natural channels. These were used in sizing the artificial 3000 feet long East Side Outfall channel in Corte Madera California. This channel, which was an essential component of the City's flood management system had been silting up every three years. By incorporating a controlled tide level wetland upstream we were able to design a self scouring channel that has required no maintenance since the project's completion in 1986.

Since 1981 PWA has used the hydraulic geometry method to size tidal channels, levee breaches, navigation channels on many other projects on the Pacific Coast. Consequently in 1994 the Corps of Engineers requested PWA to codify this method so that it could be used more generally for meso-tidal estuaries throughout the U.S. This work was carried out in the form of a design guidelines manual.

Hydraulic geometry plot ▼



Client: U.S. Army Corp of Engineers Waterway Experiment Station, Vicksburg, Mississippi

Project location: Nationwide

Period of Performance: 1994-1995

PHILIP WILLIAMS & ASSOCIATES
CONSULTANTS IN HYDROLOGY

APPENDICES

APPENDIX I

Marshes Used in the Tidal Prism Data Base

APPENDIX I

MARSHES USED IN THE TIDAL PRISM DATA BASE

The sites that were used in the tidal prism data base are all characterized by a marshplain dominated by pickleweed; channels are typically steep-sided, incised and sinuous, and slump-blocks are common. The specific sites are as follows:

1. F-G Street Marsh. This is marsh of about 10 acres at Chula Vista, San Diego Bay; only two data points from this marsh were used. It is constrained on three sides by fill that has been in place for 30-40 years. The connection to the Bay is through two 36-inch culverts, but the high tides in the marsh were found to be the same as the high tides in the Bay, and the culverts do not create a significant backwater effect. The Mean Diurnal Range is 4.3 ft.
2. E Street Marsh. This is a remnant natural marsh at Chula Vista, open to San Diego Bay and confined on two sides by fill placed 40 years ago. It contributed three points to the plots. The Mean Diurnal Range is 4.3 ft.
3. Sweetwater Marsh. This marsh is also at Chula Vista; data were taken from two areas of the marsh. The first is a remnant pristine marsh near the mouth of the marsh system; 14 points were taken from this area. Three cross sections were also taken from a larger channel connecting the marsh to San Diego Bay. This marsh has been relatively stable for 30-40 years. The Mean Diurnal Range is 4.3 ft.
4. Rush Creek. These are from the Rush Creek Marsh in Novato; cross sections were surveyed on both Rush Creek Slough and Black John Slough, above and below the confluence of the two sloughs, and on Rush Creek 120 ft downstream from the "Cemetery Marsh Outlet". Five data points are included from this marsh. The Mean Diurnal Range is 5.9 ft.
5. ESOC. This is the "East Side Outfall Channel" or Hahn Marsh at Corte Madera. The channel was dredged about 30 years ago, and has accumulated sediment since then. There is some uncertainty about whether or not it is in "equilibrium"; two of the three data points from the channel plot (on the cross sectional area vs. tidal prism plot) slightly above the average. Eliminating these points would not, however, make much difference in the regression relationships. Mean Diurnal Range is 5.7 ft.

6. Heerdt Marsh. This is the marsh just south of the Greenbrae Boardwalk; cross sections were surveyed off the boardwalk. Parts of the marsh were obliterated years ago by the construction of Highway 101, but the data used here (two cross sections) re for smaller pristine channels unaffected by the fill. Mean Diurnal Range is 5.7 ft.
7. Newark Slough. The Audubon Marsh at Newark Slough is an 80-acre marsh in South San Francisco Bay, near Dumbarton Bridge. The main slough channel in the marsh is a tributary to Newark Slough, with the confluence about 1/2 mi. upstream from the mouth. The marsh is confined on three sides by a railroad grade, a salt pond levee and old road grade, which has been breached at one point. The old marsh surface subsided 1-2 ft during the first half of this century as a result of groundwater pumping. A detailed modeling of sediment deposition shows that the marshplain is about 0.2 ft lower than it would be if subsidence had not occurred (Dr. Ray Krone, pers. comm.). The Mean Diurnal Range 8.4 ft.

APPENDIX II

Slope Stability Analysis of Tidal Marsh Channel Walls

APPENDIX II

SLOPE STABILITY ANALYSIS OF TIDAL MARSH CHANNEL WALLS

Steven M. Watry and Jay Stratton Noller

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1. INTRODUCTION

This report provides the results of a geotechnical assessment of the natural slope (angle of repose) for tidal marsh channels constructed of natural or dredged cohesive sediment (bay mud). The angle of repose, the maximum slope an earth material can remain stable, for bay mud was determined by two-dimensional slope stability analyses. These analyses were performed using a range of slopes and sediment strengths as input. Unvegetated slopes of tidal marsh channels are observed to lie within the range of 3:1 to 7:1 (horizontal:vertical). Strength is used as the material parameter because it is a measure of a sediment's resistance to deformation (i.e., a *stable* channel wall will not deform).

This report is organized into three sections. In the first section, factors contributing to or detracting from the shear strength of bay mud are reviewed. In the second section, shear strength data for bay mud are examined. In the third section, slope stability analyses are presented and discussed.

2. FACTORS AFFECTING BAY MUD STRENGTH

The strength of bay mud (natural and dredged) is influenced by several factors, including consolidation, surcharging, desiccation, cementation, and root growth. Natural bay mud gains strength from consolidation by self-weight of the sediment. A strength gain will be realized if a surcharge is applied to the sediment in excess of its preconsolidation pressure. This can be achieved by 1) construction of embankments above the desired grade; 2) lowering of the water table in the sediment thereby causing an increase in the effective stress; or 3) both 1 and 2. Desiccation of sediment will increase its strength. The most common process of desiccation on tidal marshes is by evaporation through the agents of sun, wind, and plant transpiration. Evaporative desiccation creates negative pore pressures in clayey sediments, in turn causing the near surface sediment to become overconsolidated and stiff. The result of this process is a surficial crust on the sediment. A minor gain in strength can occur due to secondary compression of the sediment. Cementation by carbonates, oxides, silica, and organic compounds will also increase strength. Plant roots bind the soil together; transpiration can create negative pore pressures that promote consolidation of the sediment, and hence increase its strength. The latter factor is probably the most important for tidal marsh channels.

In the construction of a tidal marsh plain from dredged material, the most important factor that will affect sediment strength is the method of sediment placement. If the wetland area is developed in a drained, diked containment area, the fill can be processed with grading equipment and compacted to achieve shear strengths far in excess of that obtained by natural processes, although this may create conditions unfavorable for plant growth. If tidal marsh construction occurs in undrained soils, then conditions will be adverse, if not prohibitive, to the use of compaction equipment.

3. SHEAR STRENGTH OF BAY MUD

Recent papers discussing the engineering properties of young bay muds were reviewed to obtain data for slope stability analyses. Shear strengths of bay muds range from 100 to 1,500 pounds per square foot (psf), with the higher strength values likely representing deeper bay muds (Bonaparte and Mitchell, 1979). Average total unit weight for bay mud is 94 psf (Bonaparte and Mitchell, 1979).

The engineering properties of young bay mud reported by Mitchell *et al.* (1992), were determined by vane shear, Undrained Unconsolidated (UU) triaxial tests and cone penetration tests. They reported a near constant shear strength of about 200 to 250 psf over the upper 10 to 20 ft of young bay mud. Some individual tests were as low as about 100 psf. Several individual UU tests had undrained shear strength values greater than 250 psf that are attributed to evaporative desiccation.

For soft saturated, fine-grained soils, a relationship exists between the undrained strength of the soil and the effective overburden. The relationship typically is expressed as the undrained strength divided by the effective overburden pressure (c/p ratio). Bonaparte and Mitchell (1979) note that the c/p ratios for soft, saturated soils range from 0.11 to 0.40, with most values restricted to the range of 0.24 to 0.34. Young deposits, most similar to dredged sediment, have the lowest ratios.

4. SLOPE STABILITY ANALYSES

Analyses were performed to assess the stability of tidal marsh channel slopes. Observed slope conditions and strengths were used in making an estimate of the stability of various channel configurations in bay mud. The analyses were performed utilizing the slope stability program UTEXAS3. The assumptions for the slope stability analysis are as follows:

1. The vertical height of the slope is 10 ft.
2. The slope gradient varies between 3:1 and 7:1.
3. The slope and the 10 vertical ft of material below the slope have a uniform strength.

4. Modeled failure circles do not extend more than 10 vertical ft below the toe of the slope due to an increase in shear strength of bay mud with depth.
5. A four-foot deep tension crack is present at the top of the slope.

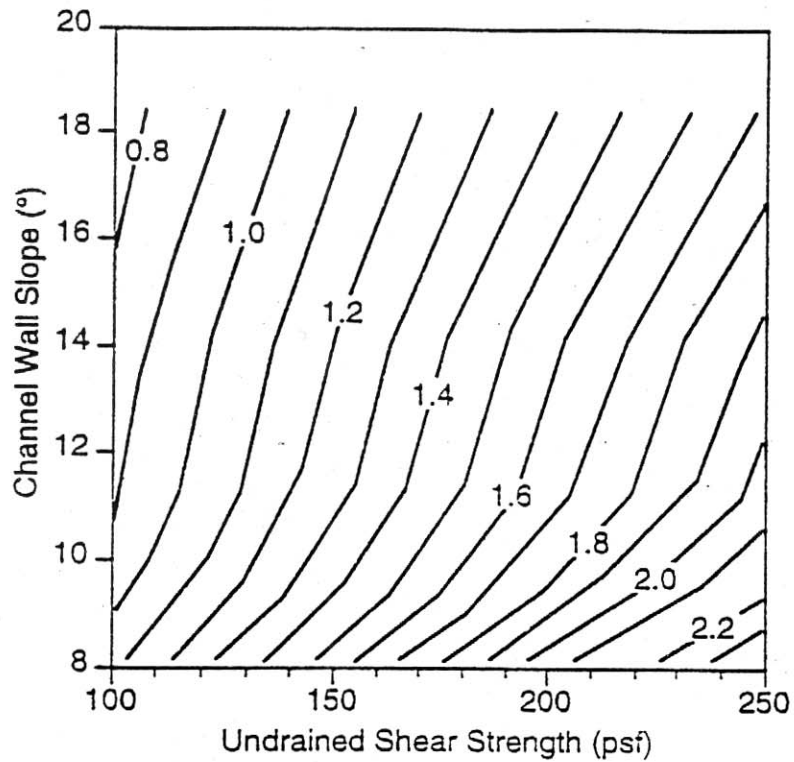
The undrained shear strength assumed for the sediment in the analyses was varied between 50 and 250 psf at 50 psf intervals. These shear strength values should closely represent different types of sediment that may be encountered in typical estuaries. The lower values would more closely approximate uppermost bay mud that is young and has not been subjected to desiccation or high consolidation loads. The higher values represent typical bay mud values as noted in the previous section.

The relationship of stability with slope gradient and undrained shear strength is shown in Figure AII-1. Lines of equal factor of safety (unity is marginally stable slope) are shown. The plot indicates that a slope comprised of very soft mud with an undrained shear strength of 100 psf only will be stable at near a 7:1 gradient. An increase of undrained shear strength to 150 psf would result in a 10 foot high slope being stable at a 3:1 gradient.

It should be recognized that highly plastic clays, which are common in many estuaries, will soften and creep when exposed to repeated cycles of wetting and drying. In the absence of supporting vegetation, the bay mud in intertidal areas will creep and likely approach a slope gradient that approximates the residual friction angle of the clay mineral that comprises most of the mud. In San Francisco Bay, for example, the clay mineral montmorillonite is common. Residual friction angles are generally 4 to 10 degrees for montmorillonite. This would result in channel walls with slopes of 5.5:1 to almost flat.

Although not modeled during this study, vegetated slopes are observed to hold up near-vertical to vertical slopes, particularly the upper section of channel walls. Hence, the presence of vegetation is considered to have a major influence on tidal channel slope stability. As mentioned earlier, the root mass of marsh plants binds and hence considerably strengthens marsh soil. According to Pestrong (1973) and Foott *et al.* (1992), root-bound mud in San Francisco has a shear strength in the range of 300 to 800 psf. Such a relatively high strength value would lie well off the graph of Figure AII-1 and have a high factor of safety, and hence a high maximum stable slope.

It follows then that tidal marsh channel slopes will chiefly vary depending on the presence or absence of vegetation. As observed in tidal marshes of San Francisco Bay, channel wall slopes are bimodal: the lower, unvegetated section of a channel wall has a low slope, whereas the upper vegetated section has a high slope.



Lines of equal factor of safety for slopes underlain by Bay mud are shown relative to tidal marsh channel wall slope and Bay mud strength.

Source: William Lettis & Associates, Inc.



Philip Williams & Associates, Ltd.
Consultants in Hydrology

Lines of Equal Factor of Safety for Slopes

Figure
AII-1

5. CONCLUSIONS

The slope (angle of repose) of tidal marsh channel walls is positively correlated with sediment strength: the greater the strength of sediment, the steeper the channel wall. The limit of tidal marsh channel wall slopes was determined by two-dimensional slope stability analyses. The slopes and sediment strengths used in these analyses are based on observed values of tidal marsh sediments from the San Francisco Estuary (bay mud). Unvegetated slopes should be expected to hold up a maximum 6:1 slope. Vegetated channel walls, however, should be expected to build near vertical to vertical slopes due to the restraint of the near-surface soils by the root mass. In conclusion, the bimodal nature of tidal marsh channel slopes is a function of the inherent sediment properties (including mineralogy and grain size) and post-depositional factors (including change in total stress, desiccation, vegetation, and cementation).

APPENDIX III

Using Tidal Energy to Erode Channels in Dredged Material

APPENDIX III

USING TIDAL ENERGY TO ERODE CHANNELS IN DREDGED MATERIAL

In some wetland creation projects, dredged material can be used to create a marshplain at elevations suitable for tidal inundation. If the material is placed too low, the result is an unvegetated mudflat; influx of fresh sediment and accretion of the marsh surface are required to create a vegetated tidal marsh. If the material is placed too high, however, there is insufficient tidal energy to create channels in the new marsh.

In order to determine the optimum elevation for placement of dredged material, two approaches were used. In the first approach, old sites used for dredged material disposal in San Francisco Bay were surveyed, and the evolution of tidal channels and elevation of the marshplain was documented. In the second approach, a tidal hydrodynamic model was used to calculate the bed shear stress on a hypothetical surface of dredged material placed at Mean High Water.

1. CASE STUDIES

1.1 Muzzi Marsh

Muzzi Marsh is located south of Corte Madera Creek at Corte Madera, in northern San Francisco Bay. The history of the Muzzi site is described by Faber *et al.* (1988). The site was part of a historic tidal marsh system that once extended over three miles along Corte Madera Creek to Ross Valley. The Muzzi Marsh area was diked in the 1950's for use as a future industrial site. In response to drying out, the marshplain subsided. In 1976, the Golden Gate Bridge, Highway, and Transportation District acquired the Muzzi property as a mitigation site. Approximately 573,450 cubic meters of dredged material from a nearby navigation channel were placed within the restoration area. A training levee was constructed to contain most of the material. A limited amount, however, was allowed to flow over the training levee to achieve an elevation gradient in the restoration site. The site was filled to an approximate elevation of 4.4 ft. NGVD in the upper portion of the marsh at the western/landward margin, and an elevation of approximately 1.0 to 2.0 ft NGVD in the lower portion near the bay. Tidal activity was restored in June 1976 by breaching the bayward dikes.

Tidal elevations at Muzzi Marsh are as follows:

Elevation (ft NGVD)	
MHHW	3.13
MHW	2.54
MTL	0.48
MLW	-1.58
MLLW	-2.64

An elevation transect was surveyed in 1977 and resurveyed 1987 and 1990 by Philip Williams & Associates, Ltd. The marshplain in the upper portion of the marsh initially subsided 1.1 to 1.5 ft from an elevation of approximately 4.4 ft NGVD in 1976 (reported by Faber *et al.*, 1988) to between 2.9 and 3.3 ft (in 1977). Since 1977, the upper marsh has risen from between 2.9 ft and 3.3 ft NGVD to between 3.1 ft and 3.4 ft NGVD in 1990. The current upper marshplain elevation is similar to MHHW.

The lower marshplain had an initial elevation of approximately 1.0 ft NGVD in 1976 (Faber *et al.*, 1988). By 1977, the marshplain had risen to an elevation of 1.8 ft NGVD, and sedimentation continued to raise the marshplain to its present elevation of 2.3 ft NGVD. The current lower marshplain elevation is between MTL and MHW.

These surveys show that the rate of sedimentation in the lower marsh is more rapid than the rate in the upper marsh. The rate of sedimentation in the lower marsh is approximately 0.5 inches/year for the period between 1977 and 1990 while the sedimentation rate in the upper marsh is approximately 0.2 inches/year for the same period.

Slough channel development can be quantified by computing the drainage density, or the length of slough channel per area of marsh (in units of ft per square ft). In Muzzi Marsh, the restoration area was divided into two areas, the upper area to the west of the training levee, and the lower area, the east to the training levee. The calculation for the upper area includes straight slough channels that were cut as mosquito ditches as well as incipient channels. The upper portion has a drainage density of 0.006 ft per square ft (or 29.0 miles per square mile), while the lower portion has a drainage density of 0.013 (or 68.6 miles per square mile). The drainage density in the lower marsh is twice as large as that in the upper marsh.

This analysis indicates that slough channel development is more abundant in the lower part of the marsh than in the upper part of the marsh. A comparison of slough channel development at Muzzi Marsh to the Corte Madera Ecological Reserve (CMER, also called Heerdts Marsh) allows for the opportunity to compare slough channel development at a restored marsh to a pristine marsh. The drainage density measured at CMER is approximately 0.010 ft per square ft (or 53.4 miles per square mile). This comparison suggests that the lower part of Muzzi Marsh (less than 2.0 ft NGVD) was placed at an elevation appropriate to develop a viable slough channel system, while the upper part of the marsh is too high for rapid slough channel development.

1.2 Alameda Salt Pond 3

Salt Pond 3 (also called FC-7 by the Alameda County Flood Control District) is a 110 acre marsh located on the north side of the Alameda Creek Flood Control Channel in South San Francisco Bay. The marsh is one of the habitat development sites built by the U. S. Army Corps of Engineers (Corps) on dredged material, and was a mitigation site for dredging activities in the Alameda Creek Flood Control Channel. Prior to 1900, the site was part of an extensive tidal saltmarsh system which formed the margin of San Francisco Bay. By the 1930's, the site was diked and used as a saltwater evaporation pond.

The U.S. Army Corps of Engineers describe changes to Pond 3 in Appendix K of the Dredge Disposal Study for San Francisco Bay and Estuary (1976). In 1965, Pond 3 was abandoned as a salt pond. In 1972, the San Francisco District of the Army Corps of Engineers breached the site to allow tidal inflow. In 1974, the breach was closed, and the Corps placed over 654,000 cubic yards of fine-grained silty clay inside the levees. Because of difficulties in observing topography during the turbid hydraulic slurries the actual elevation of the marshplain was higher than intended in part of the marsh. In 1975, the dike was breached again, and a slough channel was cut into the dredged material from the breach. Test plots of vegetation including cordgrass, glasswort, and pickleweed were initiated and monitored through 1986.

Tidal elevations at Salt Pond 3 are as follows:

Elevation (ft NGVD)	
MHHW	4.26
MHW	3.66
MTL	0.85
MLW	-1.97
MLLW	-2.48

A longitudinal profile was surveyed in 1991 from the levee separating the bay from the lower part of the marsh to approximately 3,600 ft upslope. Two elevation transects were surveyed in locations where the Corps and the Alameda County Flood Control District had previously surveyed transects. An additional transect was surveyed at a dredge material discharge location approximately 3,600 ft upslope from the bay edge of the marsh.

These surveys indicate that the upper marsh has had a net subsidence rate of approximately 0.4 inches/year between 1975 and 1991, while the lower part of the marsh has had a net sedimentation rate of 0.9 inches/year during the same period.

Slough channel evolution was analyzed using the drainage density calculation for the upper portion of the marsh (upslope of Transect B) and the lower portion of the marsh (downslope of Transect B). The drainage density in the upper portion of the marsh is 0.002 ft per square ft (or 8.6 miles per square mile) while the drainage density in the lower part of the marsh is 0.004 ft per square ft (or 20.8 miles per square mile). This analysis shows that there are at least twice as many slough channels in the lower part of the marsh as in the upper part of the marsh.

2. MODELING STUDIES

2.1 Methods

The likelihood of tidal channels developing in a marshplain filled to a given elevation can be assessed using a tidal hydrodynamic model. This has been done using the 2-dimensional model DIVAST. This model was used to calculate water depths and shear stresses on the proposed marshplain. DIVAST is a two-dimensional hydraulic and water quality model developed at the University of Bradford (Falconer and Chen, 1991). The model simulates flow through a horizontal grid using depth-averaged velocities, and solves the fluid equations of motion with a finite-difference numerical scheme.

DIVAST was applied to a hypothetical semi-circular 2nd-order drainage area of 15-acres with the marshplain at Mean High Water (2.4 ft NGVD).

The simulated area is open to tidal action along a boundary that is adjacent to a 3rd-order channel. To evaluate shear under a range of conditions, flows on the marshplain were simulated for 1) a mean tide, 2) a spring tide, and 3) a mean tidal month.

The key outputs of the model are water surface elevations and bed shear stresses (in Newtons/square meter) at each grid location for each time step. For this analysis, the distribution of shear stress over the

marshplain surface was plotted at selected times. A detailed frequency analysis of shear was performed at the location of maximum shear stress.

2.2 Results

Figure AIII-1 shows the height-duration and shear stress-duration curves for a mean tidal month in the example case. This figure shows that a marshplain elevation of 2.4 ft NGVD will be exceeded 10 percent of the time. Thus, for 90 percent of the time during a typical month there will be no water available to exert shear stress on the marshplain.

Figure AIII-2 shows a time series of maximum shear stress for a mean tidal cycle. In this case, shear stress is only generated on the flood and ebb tides preceding and following Higher High Water. Shear stresses peak at about 0.06 N/m^2 on the ebb tide, and are slightly lower on the flood tide. A similar pattern is seen on a spring tide, in which shear peaks at 0.36 N/m^2 on the ebb tide (Figure AIII-3). In both cases, shear stresses above zero occur over periods lasting less than 1 hour.

To evaluate channel formation on non-cohesive sediments, the Shields diagram was used to estimate critical shear stresses for particle diameters ranging from 0.05 to 0.5 mm. Table AIII-1 summarizes and compares the estimated critical shear stresses to the frequency distribution of shear for a mean tidal month. The results show that the shear stresses required for erosion of these particles will be exceeded less than 1 percent of the time.

The results are more difficult to interpret for cohesive sediments. Measured critical shear stresses for these sediments may range from as low as 0.02 N/m^2 to as high as 7 N/m^2 . However, most reported values fall in the 0.1 to 1.0 N/m^2 range. In a mean tidal month, this range of shear stresses would be exceeded no more than 1.5 percent of the time, and critical shear stresses greater than 0.5 N/m^2 will virtually never be exceeded.

The above results show that the shear stresses required for channel formation will occur no more than 1.5 percent of the time, and probably much less frequently for erosion-resistant cohesive sediments. These shear stresses will occur primarily during peak ebb and flood flows in spring tides, and will have durations of less than 1 hour. Little or no erosion will occur during mean tides. It is therefore unlikely that significant channel formation will occur unless the marshplain is established at an elevation that will allow more frequent inundation.

3. CONCLUSIONS

The most important lesson to be drawn from these field and modeling studies is that the finished elevation of placed material is critical to the development of proper circulation and vegetation. If the material is

placed at an elevation appropriate for a vegetated marshplain (approximately between MHW and MHHW), then a mature channel network cannot develop, and circulation will remain inadequate. A mature channel network should have 0.009 to 0.010 ft of channel per square ft of marsh area (or 50-60 miles of channel per square mile of marsh area). If such a network cannot be constructed when the material is placed, then the finished elevation must be slightly below MHW to allow the network to develop on its own.

If the material is placed too low, however, vegetation will be inhibited from invading due to prolonged inundation. In a large embayment with substantial wind fetch, wind-generated waves may accelerate erosion of both the marsh surface and shoreline.

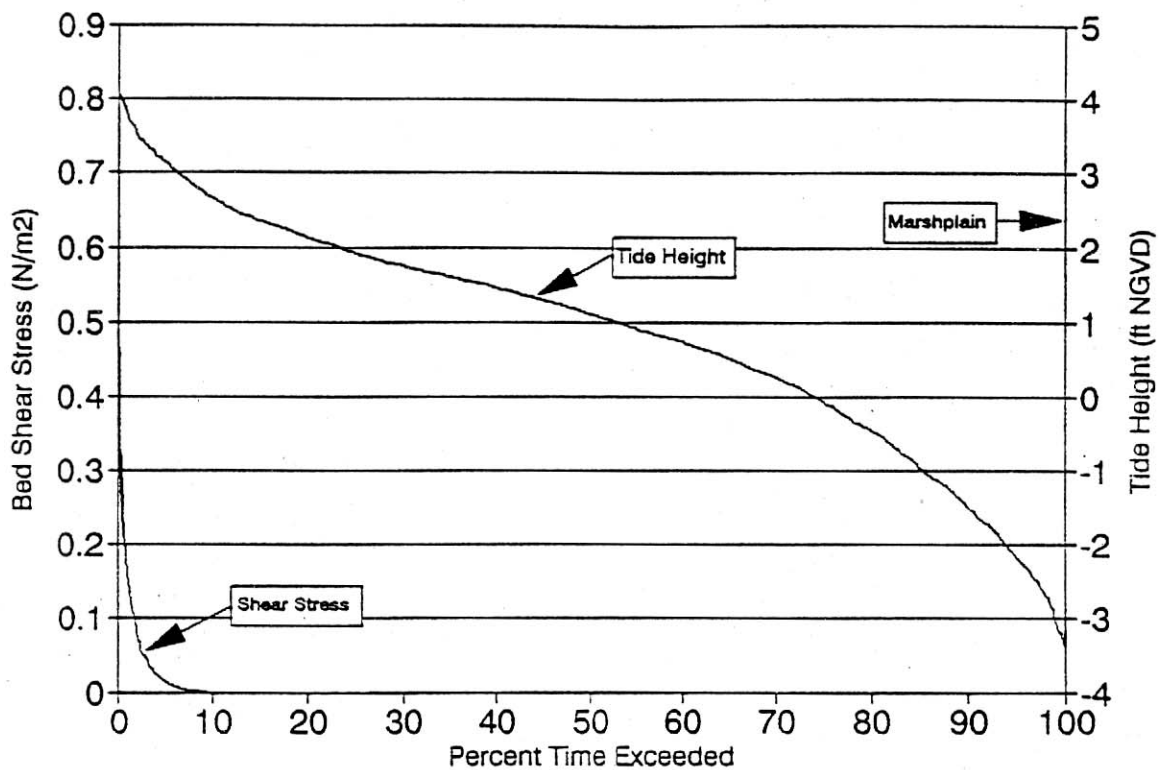
To some extent, subsidence and deposition will compensate for placement of the material at the "wrong" elevation. Subsidence of 1-1.5 ft can occur in the first year, depending on the characteristics of the material and the inundation period. If the finished elevation is below MHW, sedimentation will raise the level, but the sedimentation rate is highly dependent on local conditions.

The appropriate elevation for placement of material is thus dependent on 1) the expected rate of subsidence and consolidation; 2) the hazard of wind-generated waves; 3) the local sediment supply; 4) the designed channel density; and 5) the presence or absence of plants and animals that will affect erodibility of the material as well as deposition. A vegetated tidal marsh with a mature channel network and natural circulation pattern is most likely to result if the elevation after one year of consolidation is 1-1.5 ft below MHHW.

TABLE AIII-1

COMPARISON OF MARSHPLAIN SHEAR STRESSES TO
CRITICAL SHEAR STRESSES FOR
NON-COHESIVE SEDIMENTS

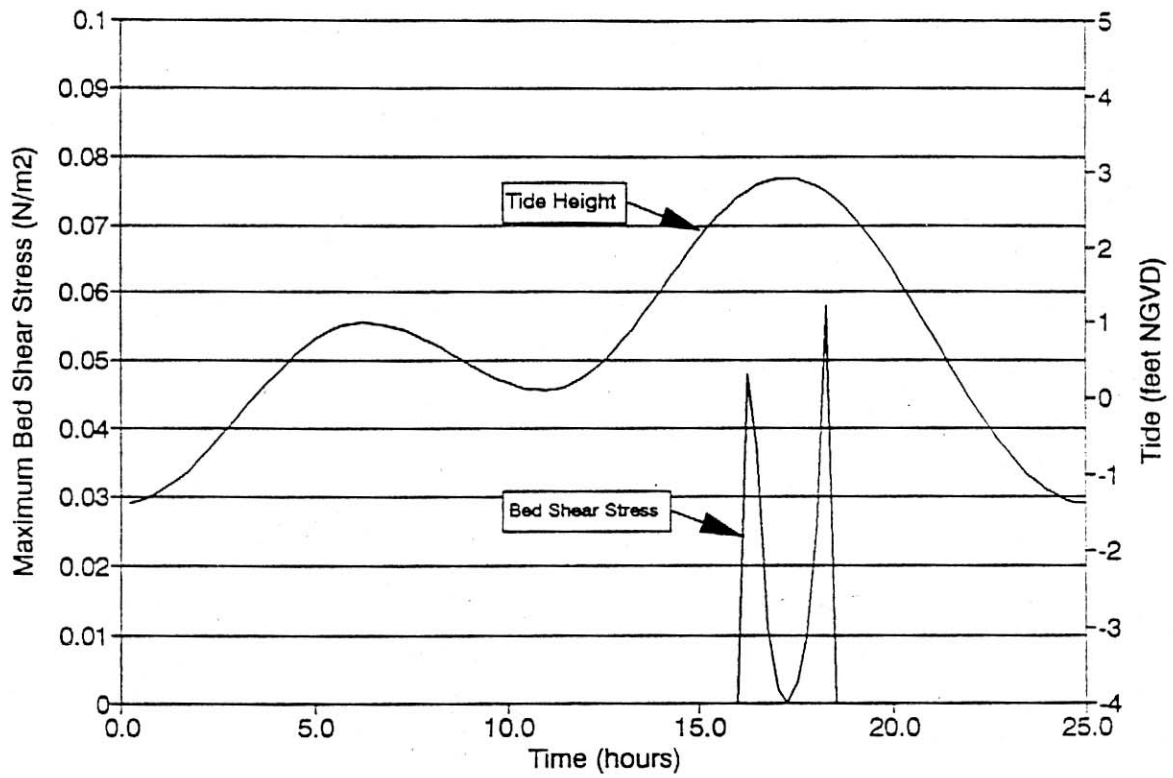
Sediment Particle Size (mm)	Critical Shear Stress (N/m ²)	Percent Time Exceeded on the Marshplain
0.50	0.30	0.4
0.25	0.20	0.8
0.10	0.16	1.0
0.05	0.15	1.1



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DIVAST 2-D Model Results of
Height and Shear Stress Duration
during Mean Tidal Month

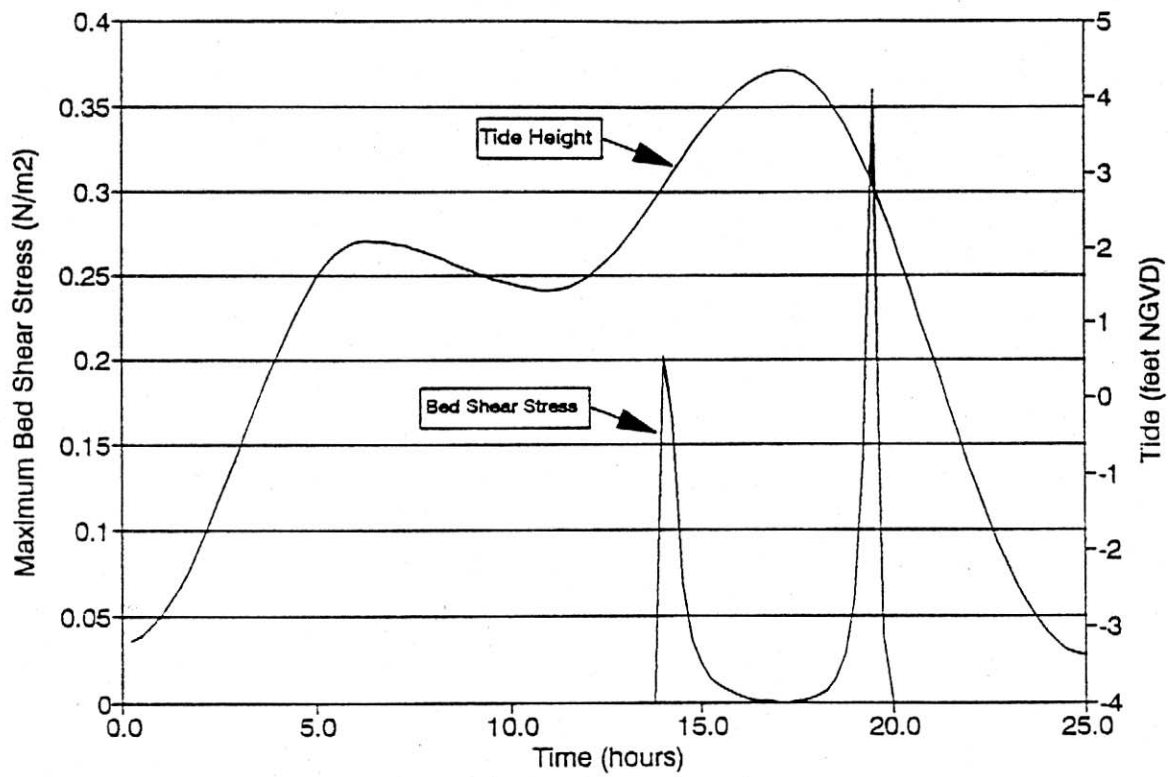
figure
AIII-1



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DIVAST 2-D Model Results of
Height and Shear Stress Duration
during Mean Tidal Cycle

figure
AIII-2



Philip Williams & Associates, Ltd.
Consultants in Hydrology

DIVAST 2-D Model Results of
Height and Shear Stress Duration
during Spring Tidal Cycle

figure
AIII-3