Hydraulic Aspects of Wetland Design

Walker, J R
Bertolotti, A
Flick, R E
et al.

1988-05-01

HYDRAULIC ASPECTS OF WETLAND DESIGN

PRESENTED AT THE AMERICAN SOCIETY OF CIVIL ENGINEERS 21 ST INTERNATIONAL CONFERENCE ON COASTAL ENGINEERING, MAY 1988.

BY:
JAMES R. WALKER, M. ASCE
ANDREA BERTOLOTTI, M. ASCE
REINHARD E. FLICK
C. ROBERT FELDMETH

21 st. International Conference
on Coastal Engineering

HYDRAULIC ASPECTS OF WETLAND DESIGN

James R. Walker[1], M. ASCE
Andrea Bertolotti[2], M. ASCE
Reinhard E. Flick[3]
C. Robert Feldmeth[4]

ABSTRACT

Tidal wetland preservation, restoration and creation have become requisites for coastal development projects in the United States. A basic approach to design of tidal wetlands is presented, stressing cooperation between regulatory agencies, biologists, engineers, and developers. Basic principles of wetland functions are explained and presented as criteria for engineering design. A description of wetlands is given to identify biological features relevant to design. Also, some key features of tides are summarized as they affect wetland design. A numerical model was used to demonstrate how tidal wetlands may be designed to conform with criteria developed by the agencies and biologists. This approach has been used on wetland designs in California, but the approach may be applicable to other areas of the world.

1.0 INTRODUCTION

Wetlands must be designed based on sound engineering principles to meet given biological requirements. Commercial and residential development along the coastal areas of the United States has increased pressure on many wildlife habitats. State and Federal wildlife agencies have been charged with preservation, enhancement and replacement of wetlands. Now, new developments in coastal areas be must done in conjunction with restoration or creation of wetlands.

The agencies must define the habitat type desired and biologists must define the conditions which will create the desired habitats. The objective is to create habitat that will support desired animal and plant life. After a site is

---

[1] Vice President, Moffatt & Nichol, Engineers, Long Beach, CA 90807

[2] Coast Engineer, Moffatt & Nichol, Engineers, Long Beach, CA 90807

[3] Oceanographer, Cal. Dept. of Boating and Waterways, Scripps Institution of Oceanography, La Jolla, CA 92013

[4] Professor of Biology, Joint Science Center, The Claremont Colleges, Claremont, CA 91711

selected, hydraulic studies are conducted in order to determine how best to achieve the desired biological setting. The wetland habitat depends in part on the tide elevations relative to the ground elevation. The ocean tide, which drives the water exchange in the wetland, has peculiar properties that influence the behavior of the water levels in the wetland. Tide control structures regulate the flow of water in and out of a wetland. Hydraulic models can simulate the flow regime in the wetland and through tide control structures. The effect of tide control structures to change wetland tide elevations relative to ground elevations is also an important design consideration.

2.0 BIOLOGICAL CHARACTERISTICS OF WETLANDS

Southern California coastal wetlands occur around bays and in estuaries and are generally restricted to narrow river valleys that were cut during periods of lower sea level in the Pleistocene era. Many of these wetlands are exposed to daily tidal action. The rise and ebb of water in tidal marshes produces a zonation of vegetation types determined by both physical and biotic factors. Other wetlands persist where the tidal range is muted by culverts or restricted by tide gates. Wetlands exist because the soils remain saturated throughout most of the year. These wetland areas are characterized by an assemblage of plants and animals, an ecological community, adapted to the particular conditions of this transition area between salt water and land.

At a particular ground elevation in a wetland, there is an associated duration of inundation by tides and salinity in the soil. Wetland plants grow in areas where they are best suited to resist the inundation by tides and soil salinity. Mahall and Park (1976) examined the transition between cordgrass (low wetland) and pickleweed (mid wetland) in wetlands in northern San Francisco Bay and found tidal inundation to be the most important factor determining their distribution.

A typical Southern California coastal wetland is composed of a low wetland community characterized by dense stands of cordgrass (Spartina foliosa). Cordgrass normally occurs between mean lower high water (MLHW) and mean higher high water (MHHW) (Zedler, 1982), as shown schematically in Figure 1. At lower elevations, mud flats may support eelgrass (Zostera marina) and often mats of various algal species such as sea lettuce (Ulva).

At elevations above the low wetland, a mid and high wetland vegetative association is present. Common pickleweed (Salicornia virginica) is by far the most important plant species in terms of biomass. It normally ranges from MHHW to about 0.6 meters (2 feet) above extreme high water (EHW). Common pickleweed is abundant down to the low wetland and can often occur with cordgrass in soils that are wet by each high tide.

Also present in the mid wetland association are a number of other plants such as saltwort (Batis maritima), annual pickleweed (Salicornia bigeovii) and Jaumea carnosa. High wetland associations include common pickleweed and sea blite (Suaeda californica). These assemblages extend up to an elevation of about 0.6 meters (2 feet) above MHHW.

The transition from mid wetland to high wetland is less distinct. Soil moisture decreases in the high wetland and soil salinity increases. Shoregrass, saltgrass, and glasswort appear to be more tolerant of the drier soils of this higher wetland zone. A summary of wetland vegetation with respect to the elevation of the tide ranges is given in Table 1.

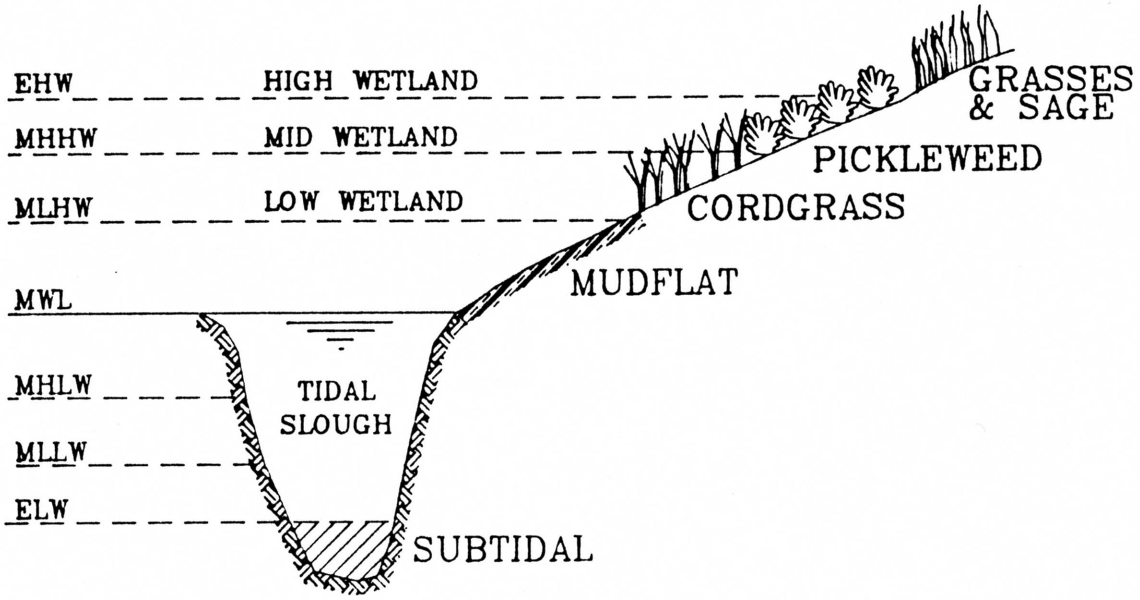

Figure 1 Typical Southern California Wetland

TABLE 1

Division of Wetland Vegetation by Elevations of Tide Ranges

TIDE RANGE	HABITAT NAME	TYPE OF HABITAT
Above EHW	High Wetland	Grasses and Coastal Sage Scrubs
MHHW to EHW	Mid Wetland	Pickleweed, Salt Wort, Annual Pickleweed and Sea Blite
MLHW to MHHW	Low Wetland	Cordgrass
MSL to MLHW	Mudflat	Eelgrass, Algae and Sea Lettuce
Below MSL	Subtidal	Marine habitat

In the mid and high wetland areas, marsh plants provide cover and foraging material for many invertebrates. Birds, such as the Clapper Rail, also utilize this cover in order to forage on burrowing crustaceans. Small snails occur on the substrate surface. Crabs and shrimp burrow in the substrate within the vegetational cover.

At high tide, mudflats are a foraging area for fishes and large wading birds, such as herons and egrets. At low tide, the exposed mudflat becomes a foraging area for shore birds. Fishes forage in the mudflat zone and up into the low wetland. These fishes form an important source of food for fish-eating birds, such as herons, egrets, and terns.

Horn (1976) showed that the fish species diversity for a bay or an estuary is proportional to its size. The relationship of bay size to species composition is shown in Figure 2. Fish diversity is an index of habitat quality; the more fish species present, the better the system is as an environment for bay-wetlands plants and animals. Other factors such as water depth, habitat diversity, pollution load are also important. Bay systems of various sizes, where the tidal regime is muted by culverts or other restrictions, can be evaluated in terms of their fish assemblages (Feldmeth, 1980 & 1986).

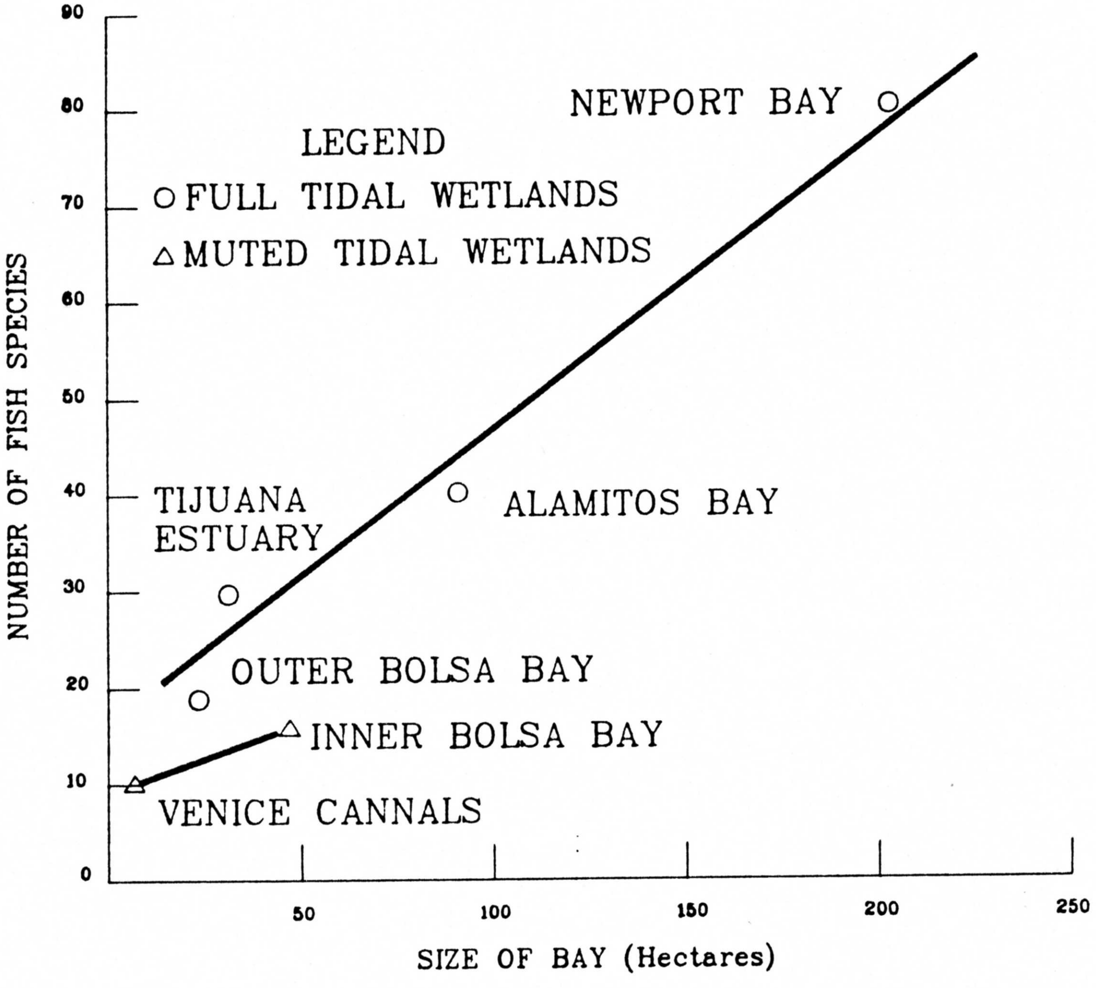

Figure 2 Number of Fish Species versus Area of Bay

3.0 TIDE CHARACTERISTICS

General tide characteristics in Southern California are presented to outline features relevant to the hydraulic design of wetlands. Tides are a well studied phenomenon and are only summarized here to illustrate their influence on design of wetlands.

Tides along the California coast are mixed semidiurnal and show a marked diurnal inequality and extreme tide ranges approach 3 meters (10 feet). A common characteristic of California tides is that the lower-low water almost always follows the higher-high water after a time interval of about 7 hours. The semidiurnal peak breaks the rising tide such that there are about 17 hours between lower-low water and higher-high water. In Figure 3, the average rate of water elevation change is plotted versus the elevation change between high and low tide for the 1983 tide record at San Diego, California. As shown in the figure, the greatest water level changes and highest tide ranges occur during ebb period. The peak flow velocities in a bay entrance will be greater during ebb flows than flood flows. This may have an effect on sediment transport and on altering the water elevations in a wetland because of the non-linear nature of tidal hydraulics.

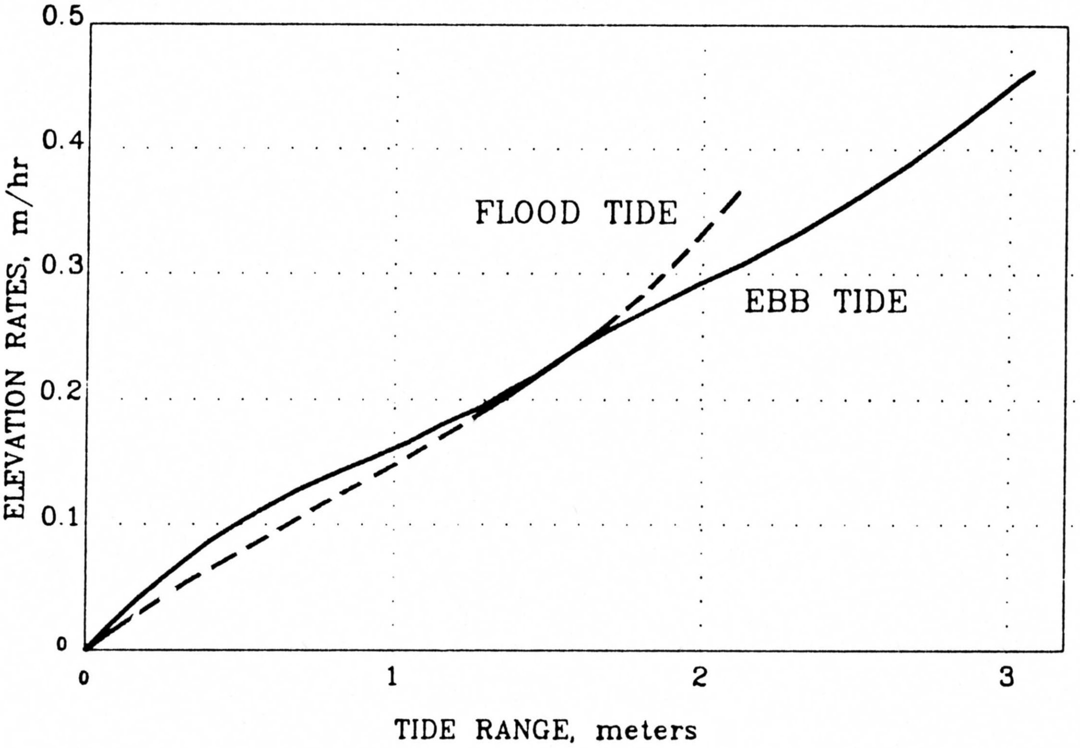

Figure 3 Water Elevation Change Rates versus Tide Range for Southern California

Variations in the tide also have a yearly cycle. Higher-high tides tend to occur in the morning during winter and in the evening during summer. Changes in the times of day of high and low tide during the year lead to significant changes in wetlands exposed to sunlight. Figure 4 shows monthly averages of the percentage of daylight hours (taken as the time from sunrise to sunset) the tide remains below MHHW, MSL and MLLW. Maximum intertidal exposure to sunlight occurs from February through April, with tide below MSL about 65% of daylight hours. There is a marked decrease in exposure to a minimum of about 25% during September.

Zetler and Flick (1985a, b) describe the cyclical variations of predicted maximum monthly high tides for the period 1983-2000. Besides the summer-winter cycle, they identify a 4.4 year variation and an 18.6 year cycle that characterize the west coast tides. The 4.4 year period arises from a modulation of the lunar perigee cycle while the 18.6 year variation is associated with the lunar node cycle. These periods increase the tide range about 0.3 and 0.15 meters (1 and 0.5 foot) respectively. During peak tides within the 4.4 year cycle, the winter and summer maximum ranges can exceed the spring-autumn ranges by about one meter (3 to 4 feet). This effect also tends to obscure the variation in seasonal mean sea level which tends to be low in April and higher by about 0.15 meter (0.5 foot) in September (Flick and Cayan, 1984)

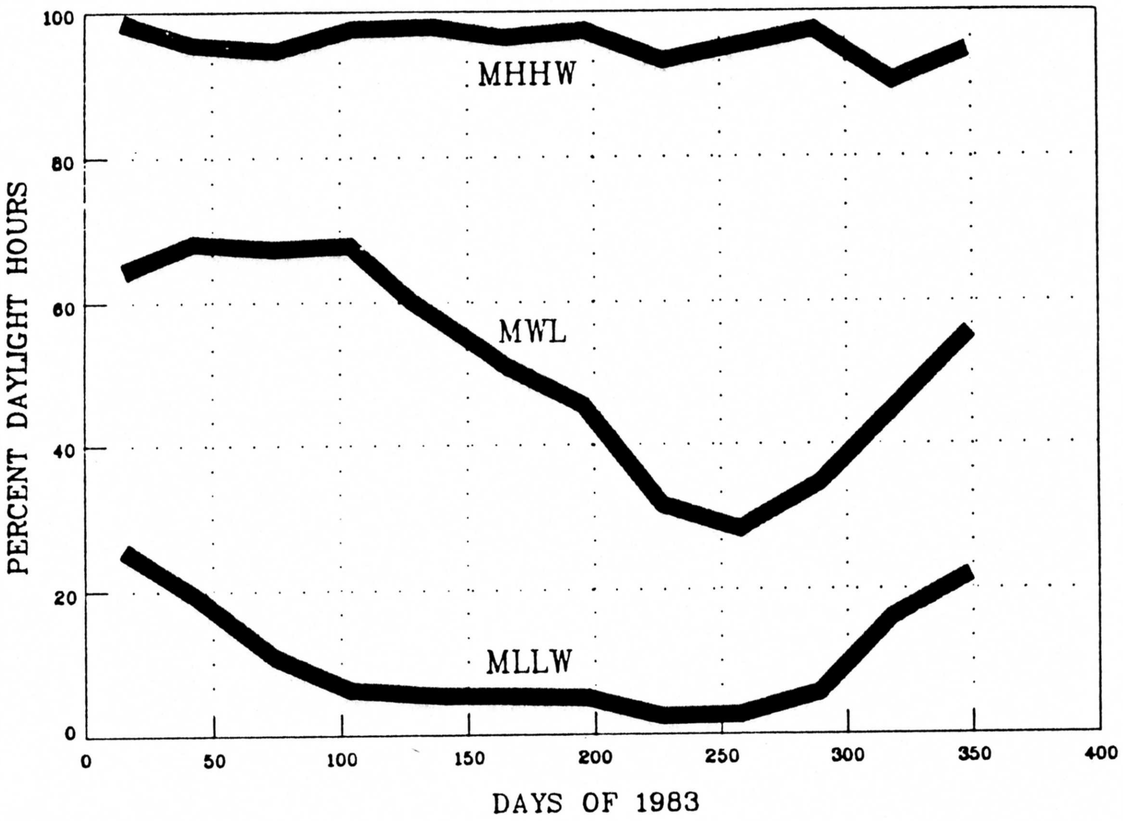

Figure 4 Percent of Daylight Hours that the Tide Remains below MHHW, MSL and MLLW

4.0 DESIGN ANALYSIS AND METHODS

4.1 Principles

Perhaps the most important design consideration is the relationship of the tide range with respect to the ground elevation inside the wetland. Changing either the tide regime or the ground elevations can significantly effect the nature of the wetland. Scour and siltation of wetland channels is also an important design consideration that includes an evaluation of flow regimes and of soil types. In wetlands that have reduced tidal flushing or are near a source of pollutants, water circulation and quality need to be considered. Finally, in newly created wetlands, colonization or plantation of flora and fauna need to be evaluated in view of the particular restoration goals.

In California, wetland restorations are founded on goals specified by wildlife agencies such as the Department of Fish and Game, National Marine Fisheries and the Fish and Wildlife Service. Other agencies that can participate are the California Coastal Commission, the Audobon Society and the Army Corps of Engineers. While no specific agenda exists for developing design goals and criteria, some guidelines can be followed such as those proposed by Smith (1983) and Williams and Harvey (1983).

As described previously, the relationship between tide range and ground elevations provides a zonation of vegetation that characterizes a wetland. Wetlands can have tide regimes and sea levels that are different from those in the open ocean. This is an essential consideration in wetland design. Friction and flow restrictions induce energy loses in tidal flow that give rise to reduced amplitudes and phase lags in the tides of inland water bodies. Some harbors or bays experience resonant conditions in which the amplitude of the tides is larger than in the ocean. In muted tidal wetlands, however, the energy dissipations at the tide control structure tend to suppress resonant oscillations and, in general, larger reductions in amplitude are accompanied by greater phase lags. Under some conditions, the mean water level in the wetland will be different than in the ocean.

The ground elevations in a wetland should be designed considering stable soil slopes and the possibility for scour and siltation of the channels. Myrick and Leopold (1963) applied the concept of equilibrium profiles developed for inland rivers to describe the hydraulic geometry of tidal channels. These equations relate the water surface width, mean depth and mean velocity to the discharge. Pestrong (1965) used the same equations to characterize the drainage patterns of tidal marshes in South San Francisco Bay, California. In the design of muted wetlands, channels that are initially sized close to the equilibrium profile can be expected to have less changes over time than channels that are of other sizes. Adding new wetland areas to existing wetland can induce scour in existing channels.

Wetlands with a small tidal prism in relation to the total water volume, or wetlands that are near a source of pollutants, can promote unfavorable water quality and circulation for the animal and plant communities. The accumulation of nutrients such as nitrogen and phosphorous used in fertilizers can promote undesirable algal blooms.

In newly created wetlands, the flora can be established by either natural colonization or by planting. The desired fauna, instead, can only be introduced by natural colonization. The type of hydraulic connection between the new wetland and the ocean should consider the passage of plant seeds and marine animals, such as fish and crustaceans. This is important were natural plant colonization is desired and were the wetlands are to function as spawning areas for fish.

4.2 Hydraulic Modeling

A numerical model based on work by Fisher (1977) was developed to analyze tide elevations and flow velocities in wetlands subject to an ocean tide. The hydraulic system is divided into a series of basins and channels. The water level in the basins and the flow velocity in the channels are related through the conservation of mass and conservation of momentum equations. These equations are solved for one-dimensional flow by the method of finite differences. The model performs a time domain simulation and calculates tide elevations and flow velocities at specified time step intervals.

The model, called Hydrodynamic Circulation Model (HCM), employs an implicit routine, where the water elevations and velocities are related to each other and to their present values through a system of simultaneous non-linear equations. The equations are solved iteratively using a Newton-Raphson algorithm. One-dimensional differential equations are used to express the conservation of mass and momentum in an open channel. The equation are as follows:

Mass: $b(dy/dt) + A(du/dx) = 0$
Momentum: $du/dt + g(dy/dx) + gku|u| = 0$

where:
t = time
x = horizontal distance
y = water surface elevation
u = velocity in x direction
g = acceleration due to gravity
b = surface width
A = cross-sectional area
k = friction coefficient

The convective acceleration term, $u(du/dx)$ which is part of the conservation of momentum equation, was omitted in the model. Including this term significantly increases the computation load and does not have a significant effect on the results.

The friction coefficient is derived from Manning's open channel equation and has been modified to include an entrance and exit energy loss term as follows:

Friction Coefficient: $k = Kx + Ke + (n/1.486R^{2/3})^2$

where:
Kx = 1.0 (common exit loss factor)
Ke = entrance loss factor
n = friction coefficient
R = hydraulic radius

The hydraulic features of an area are included in the model through a number of user-selected parameters. These include the length, width and depth of channels, the friction associated with the type of channel bed, the slope of the channel banks, the storage curves of basins, the tide properties of the ocean or driving body of water, and the type and geometry of the tide control structure.

The friction of the channel beds and concentrated head losses of restrictions to flow can be derived from published values. However, calibration of these parameters with field measurements from a hydraulic area similar to that being modeled provides more reliable values. The HCM model has been used for design of Anaheim Bay and Bolsa Chica wetlands in California (Moffatt & Nichol, Engineers, 1987a and 1987b)

4.3 Tide Control Structures

Tide control structures can be used in wetland restoration projects to control the ocean tide and produce specific tide properties within the wetland. Tide control structures can vary from a simple pipe culvert through a dike to more complex systems that have flap gates and overflow weirs that require manual or automatic operation. Usually, the complexity of the tide control system is directly related to the amount and type of change induced to the ocean tides.

A basic muted wetland comprises a dike, which separates the wetland from the source of ocean water and protects surrounding lowland areas from flooding, and one or more culverts, which allow for tidal flow between the ocean and the wetland. In this system, the flow area of the culverts and the invert elevations can be selected to produce the desired response. Check valves, typically in the form of flap gates, can be used in tide control structures to change the mean water elevation in the wetland. Flap gates can be installed on one or several culverts comprising the tide control structure depending on the amount of sea level control desired.

4.4 Maintenance of Tide Control Structures

Tide control structures are subject to gradual deterioration by being exposed to environmental conditions. The maintenance of tide control structures is important in order to keep the water elevations in the wetland within the desired range. Mussels, barnacles and other marine organisms will grow at the entrance as well as inside the culvert. This increases friction to flow and reduces the flow area. For culverts with flap gates, marine organisms can grow on the flap and culvert entrance, allowing water to leak when the flap gate should be closed. Flap gates have tendencies to restrict low flow out and to remain open with leaks for inward flow. Pinch check valves may be considered as an alternative with more positive control.

4.5 Determination of Tidal Elevations

Tidal elevations are measured by the National Oceanic and Atmospheric Administration (NOAA). Data are averaged over an 18.6-year tidal epoch to establish reference elevations such as MHHW, MLLW and MSL at the gauge station. Tide elevations in wetlands are a function of the connection with the ocean and can be different than tide elevations in the ocean.

A technique was developed to predict reference tide elevations in wetlands with tide ranges different than those in the ocean. The tide data for the Los Angeles station are used as an example. The distribution of tide elevations for a 18.6-year epoch was determined from data published by NOAA. The data was plotted as percent time of exposure versus tide elevation as shown in Figure 5; this format can be useful to wetland biologists. For the purpose of numerical modeling, a hypothetical 14-day mixed tide was developed so that it would reproduce the distribution of a 18.6-year tidal epoch. The mix between high and low tides as well as diurnal and semi-diurnal features was varied to achieve the desired distribution. This 14-day tide was used in the model analysis to determine the tidal distribution inside a wetland. In this manner, non-linearities with storage curves and hydraulic losses would be included in the prediction.

From the distribution of a 18.6-year period of tide elevations given by NOAA, it can be determined that ground at an elevation of MHHW is exposed 95 percent of the time, at MSL it is exposed 50 percent and at MLLW 5 percent. In a tidal wetland, these percentages give rise to the habitat zonations previously described.

The distribution of tide elevations inside a wetland can be defined using numerical models such as the HCM. The MHHW elevation inside a wetland is then identified as the elevation at which the ground is exposed

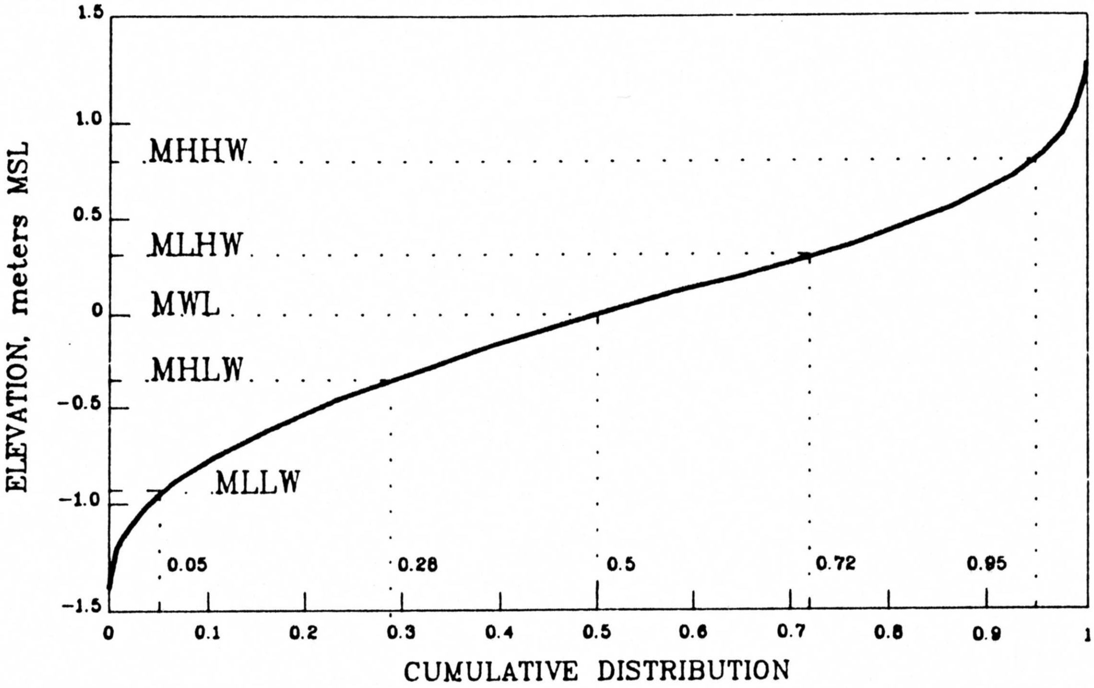

Figure 5 Percent Occurrence of Water Elevation
At or Below a Given Level

95 percent of the time. The definitions of MWL and MLLW follow a similar form, where ground at MWL is exposed 50 percent of the time and at MLLW is exposed 5 percent of the time. In this method, shown in Figure 6, the tidal elevations in a wetland are related to the type of hydraulic connection between the wetland and the ocean.

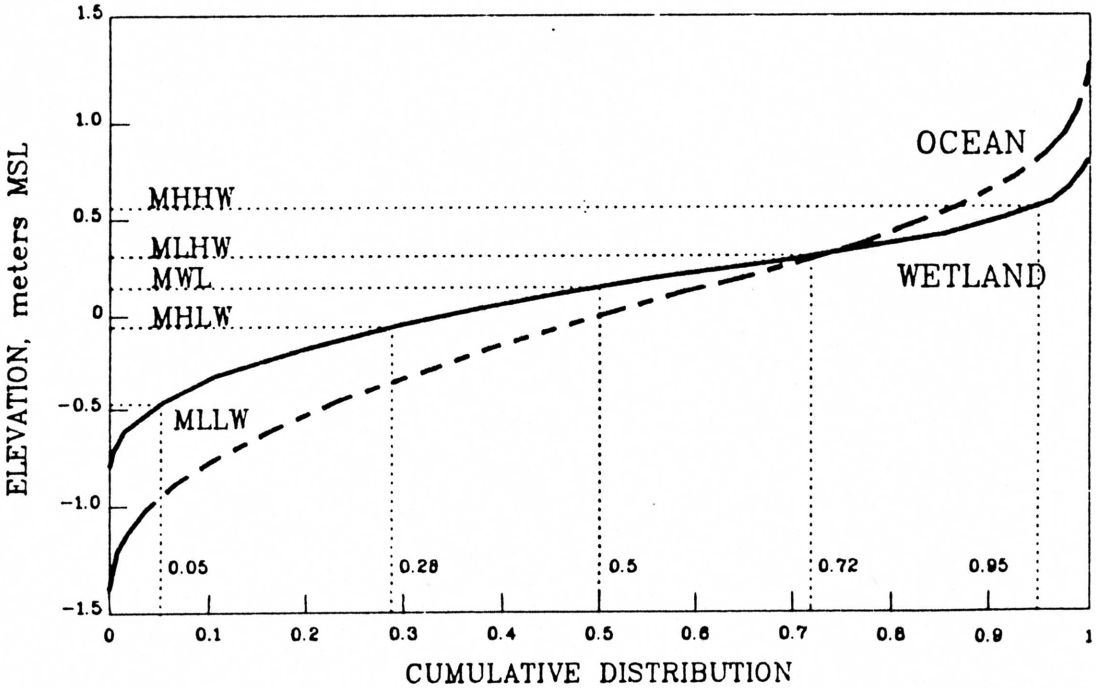

Figure 6 Method for Determining Tide Reference Elevations
in a Wetland

4.6.2 Invert Elevation of Culverts

The invert elevation of a culvert is the distance from the bottom of the flow area to the elevation datum. The invert elevation determines the minimum elevation that a wetland can drain and also whether a given culvert flows with a free surface. The effect of varying the invert elevation of wetland tide is shown in Figure 8. When the invert of the culvert is fairly deep, the culvert has a full flow section throughout the tide range. However, as the invert elevation is raised, the culvert will flow partially full with a free surface at low tide. The creation of a free surface affects first the elevation of the MLLW in the wetland by raising it higher than with a full section. The elevations of MWL and MHHW do not respond to changes in invert elevation as soon as MLLW. Further raising the invert elevation affects the MWL elevation in the wetland by raising it above MSL in the ocean. At higher invert elevations, the MHHW elevation in the wetland is reduced.

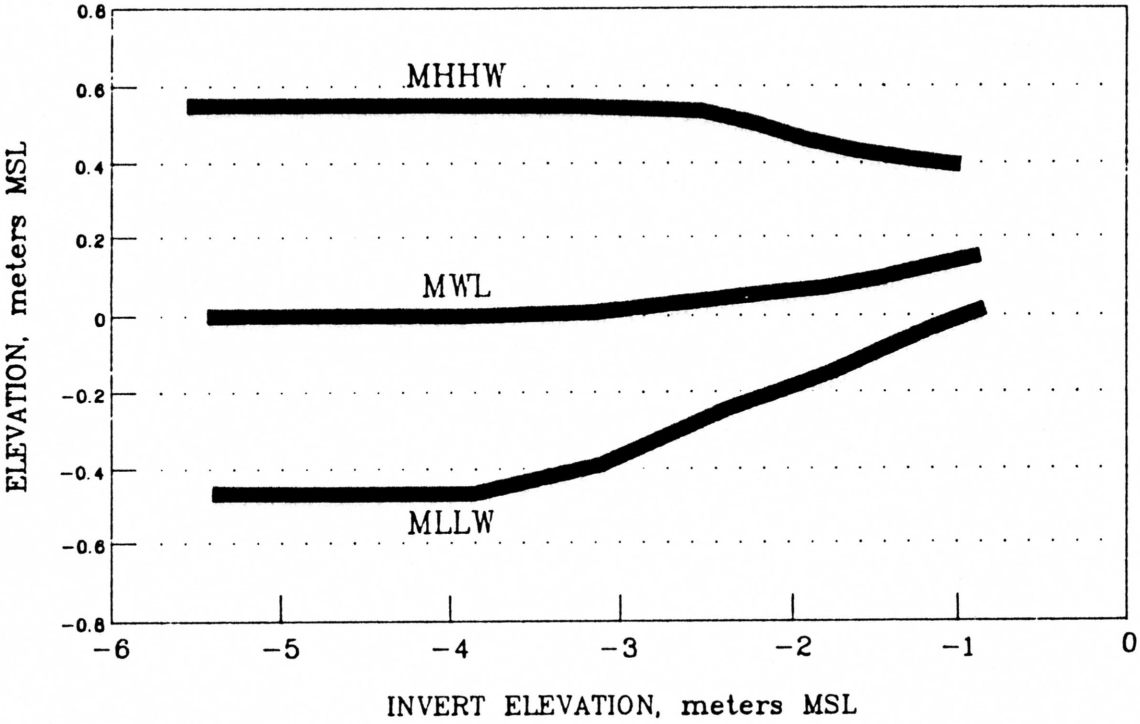

Figure 8 Effect of Culvert Invert Elevation on Wetland Tide Elevations

4.6.3 Culvert Roughness

The friction factor for a culvert depends on the type of material used in construction as well as on marine growth inside of the culvert. Values of friction factors for new culverts can be found in many references (such as Chow, 1959). However, increase in friction due to organic growth inside the culvert is more difficult to determine. An analysis of the effect of the friction factor on the wetland tide is shown in Figure 9. For a new concrete culvert, for example, Manning's "n" can vary from 0.011 to 0.013 (Chow, 1959). Experience with analysis of culverts colonized by marine growth indicated a friction factor of 0.04 to 0.06 (Moffatt & Nichol, Engineers, 1987b). The growth also reduces the culvert flow area which further restricts the flow.

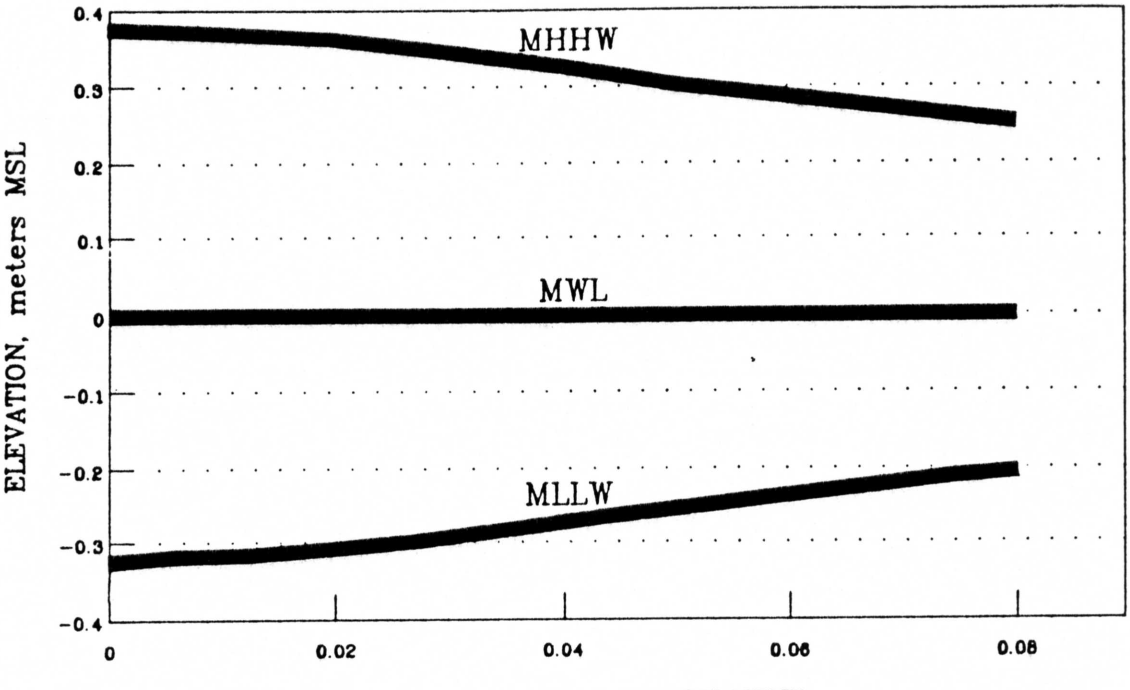

Figure 9 Effect of Culvert Roughness on Wetland Tide Elevations

5.0 FINDINGS

- In wetland creation or restoration, the goals and criteria must be established by the agencies in charge. Then biological criteria and sound engineering principles can be used in the creation or restoration of wetlands.
- Wetland creation or restoration goals should be defined by habitat type rather than by ocean tide ranges.
- Wetland habitats can be defined by the relative tide and ground elevations as well as soil conditions.
- Tide elevations inside a wetland can be defined from a water elevation distribution in the wetland. Ground at MHHW will be exposed 95 percent of the time, at MSL it will be exposed 50 percent of the time and at MLLW 5 percent of the time.
- Hydraulic numerical models are an essential tool for the analysis of wetland projects. The models provide an accurate and cost-effective method for evaluation of tide ranges in wetlands with varying ground elevations and type of hydraulic connections and controls.
- Tide characteristics should be evaluated to assess the impact of tide control structures on wetlands. In particular, during field survey and tide measurements, the various cycles of the tides should be considered to include seasonal and longer-term influences.

- The size and invert elevation of culverts as well as the topography and channel dimensions are very important parameters in the design of muted tidal wetlands.
- The long term effect of a wetland design should be investigated. Factors that will need to be considered include sea level rise, land subsidence or upheaval, sedimentation, and biofouling of tide control structures.

ACKNOWLEDGEMENTS

The design approach and model development presented in this paper came from designs of wetlands and field studies of existing wetlands. It is a summary of a larger wetland design study. The designs include the Anaheim Bay Mitigation Project for the Pier J expansion at the Port of Long Beach and the Bolsa Chica wetland development project for Signal Landmark. The authors extend their gratitude to Dr. Andrew Gram of Moffatt & Nichol, Engineers for his participation and development of the numerical model.

REFERENCES

Feldmeth, C.R. "Survey of inner and outer Bolsa Bays: recolonization and recruitment study", Unpublished report submitted to Signal Bolsa Corp., 1980, 30pp.

Feldmeth, C.R., "Biological resources of the Venice Canals", Report to Phillips Brandt Reddick for the City of Los Angeles Planning Department. 1986, 18pp.

Fisher, H. B., "A Numerical Model of the Suisun Marsh, California", Proceedings from the 17th Congr. Int. Assoc. Hydraul. Res. held at Baden-Baden, Germany 1977.

Flick, R.E. and D.R. Cayan, "Extreme Sea Levels on the California Coast", Proc. 19th Coastal Eng. Conf., Amer. Soc. Civil Eng., 1984, p. 886-898.

Horn, M.H., "Numbers of species and faunal assemblage of marine fishes in California Bays and Estuaries", Bulletin of S. Calif. Acad. Sci., 1976, 75:159-170.

Mahall, B.E. and R.B. Park, "The ecotone between Spartina foliosa Trin. and Salicornia virginica L. in salt marshes of northern San Francisco Bay. I. Biomass and production. II. Soil water and salinity. II. Soil aeration and tidal immersion", J. Ecol., 1986, 64:793-820.

Moffatt & Nichol, Engineers, "Anaheim Bay Mitigation Project" prepared for the Port of Long Beach, March, 1987.

Moffatt & Nichol, Engineers, "Bolsa Chica Project: Hydraulic Design Approach for Muted-Tide Wetlands", prepared for Signal Landmark, Inc., December, 1987.

Smith, David D., "A Practical Evaluative Procedure for the Design of Coastal Wetland Restoration Projects", Presented at the Coastal Zone 83 conference in San Diego, California, June, 1983, Vol II, pp. 1477-1487.

Williams, Philip B. and H. Thomas Harvey, "California Coastal Salt Marsh Restoration Design", presented at the Coastal Zone 83 conference in San Diego, California, June, 1983, Vol II, pp. 1444-1456.

Zedler, J.B., "The ecology of Southern California coastal salt marshes: A community profile", U.S. Fish and Wildlife Service, Biological Services Program. Washington D.C. FWS/OBS-81/54, 1982, 110pp.

Zetler, B.D. and R.E. Flick, "Predicted Extreme High Tides for California, 1983-2000", Jour. Waterway Port, Coastal and Ocean Eng., Amer. Soc. Civil Eng., 1985a, v. 111, n. 4, p. 758-765.

Zetler, B.D. and R.E. Flick, "Predicted Extreme High Tides for Mixed Tidal Regimes", Jour. Phys. Oceanog., 1985b, v. 15, n. 3, p. 357-359.