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Hypsographic, Hydro-hypsographic and Hydrological Analysis of Coastal Bay Environments, Great Machipongo Bay, Virginia

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ABSTRACT

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The Delmarva Peninsula is located on the mid Atlantic Coast Plain of the United States. The Atlantic coast of the Delmarva Peninsula is a typical coastal compartment with five landscape elements described by Oertel and Kraft (1994). Behind each element are coastal lagoons and bays with rich benthic and aquatic ecosystems. Environmental quality of these systems is strongly dependent on the exchange of water over benthic subenvironments of the bay floors. Hypsometric analysis of drainage basins is an organizational tool that may be used for quantifying the relative distribution of drainage-surface areas at different elevations.

Hydro-hypsographic curves may be used to show the relative distribution of benthic-surface area at different depths. Depth variations among subenvironments are linked to the complex hypsometric characteristics that have resulted from the transgressive reworking of relict antecedent surfaces. Very shallow areas provide optimal sites for wetland colonization. Hypsographic curves of the Great Machipongo lagoon show that about 30% of the basin is colonized by marsh. Almost 50% of the benthic-surface area has potential for colonization by submerged aquatic vegetation (SAV). However, turbidity caused by currents and bay waves limits light for primary production. Since basin topography is quite variable along the mid Atlantic coast, sea-level rise and hydro-hypsography may have a stronger influence on wetland decline ("health") than anthropogenic stresses.

The exchange of water between bays and the coastal ocean is related to the hypsographic characteristics of the tidal prism and the whole basin prism (volume hypsography). The volume-hypsograph of the Great Machipongo lagoon illustrates that the tidal prism accounts for 54% of the lagoonal prism. The relatively rapid hydraulic turn-over time for the lagoon may be an end-member for a suite of hypsographic curves from well-flushed lagoons to poorly flushed lagoons.

ADDITIONAL INDEX WORDS: *Hypsography, coastal lagoon, flushing, benthic environments*

INTRODUCTION

The purpose of this study was to determine the influence of hypsometric relationships (h/H, a/A) in a lagoonal basin on flushing and the distribution benthic environments. The following discussion is a brief review of concepts and definitions used in basin geometry and hypsometry.

"Drainage area" is defined as an area of land delineated by a network of runoff pathways to a common local base level (Figure 1). The boundaries of the drainage area are defined by the limits of the runoff pathways. Since drainage area is only a two-dimensional attribute of a land surface, the term "drainage surface" is used to include the topographic attributes in a drainage area. The relief in a drainage area gives a third dimension to the drainage surface. The relief on a drainage surface is the vertical distance between the maximum elevation in the area and the local base level. Depressions in the land surface caused by fluvial erosion have been called drainage basins. While the term drainage basin is generally used to describe the surface of the drainage area, there are several prisms bounding the surface.

The "solid-material prism" is defined as the volume of material (sediment and rock) located *below* the drainage surface and between the highest and lowest elevations of that surface. The solid-material prism has a large volume when the drainage surface area is at a high elevation above base level. The solid-material prism has a small volume when the drainage surface area is at a low elevation. In fluvial systems, the entire surface is not lowered uniformly by erosion. The area above the axis of the stream has the greatest amount of material removed, whereas progressively lesser amounts are removed from surfaces away from the channel axis. Removal of material from the solid-material prism increases the amount of void area between the valley walls. The "void prism" is defined here as the volume of void space located *above* the drainage surface, and between the highest and lowest elevations of the drainage basin.

Streams and rivers are the main agents excavating material from a drainage area producing depressions in the surface (valleys and drainage basins). Strahler (1952) intro-

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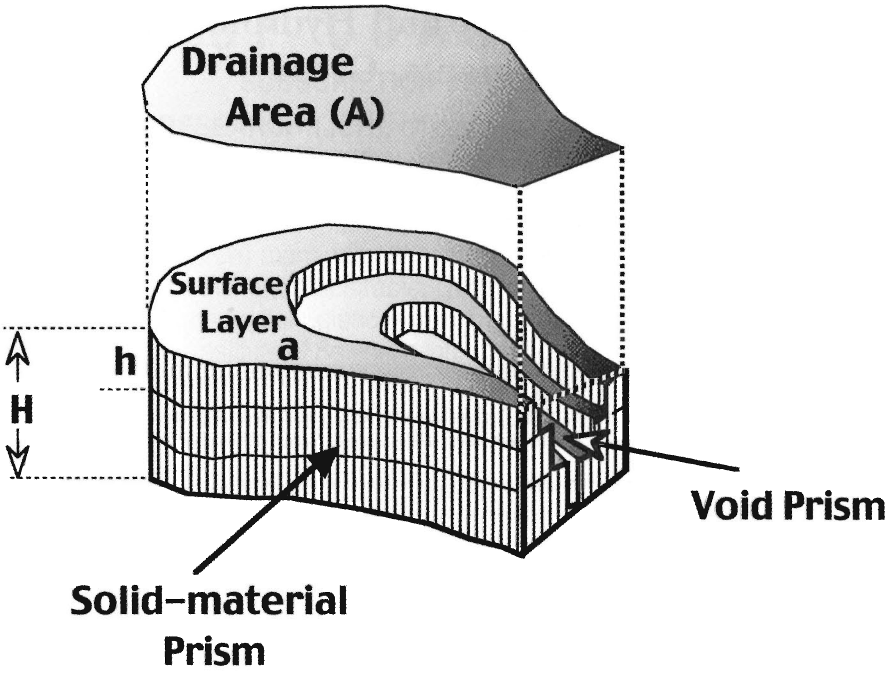

Hypsography (Solid-material prism)

$Y = h_m/H_m, \quad X = a_m/A_m$

Hydro-hypsography (Void prism)

$Y = h_v/H_v, \quad X = a_v/A_v$

Figure 1. Sketch of drainage basin illustrating terminology used for describing surfaces and three- dimensional prisms.

duced the term hypsometry to study the volume of material stored above base level in drainage basins. He integrated volume layers above the base level by comparing land-surface areas with their respective elevations. During early stages of evolution, fluvial drainage basins have large areas of elevated land surfaces. As material is removed by mass wasting and fluvial processes, the percentage of elevated-land surface decreases in proportion to the increase in low-elevation surfaces. These relationships can be illustrated in hypsographic curves that compare fractions of basin elevation with the respective fractions of basin land-surface area. Since, the entire drainage area of a basin occurs between the highest point and the basin's base level, STRAHLER (1952) equated the maximum surface area (A) with the base elevation of a basin. At the highest elevations, only small amounts of surface area remain. Conceptually, a hypsometric curve represents the elevation patterns of land area remaining after solid materials have been eroded and transported out of a drainage basin. The shape of the curve is a surrogate of the morphologic maturity of a drainage basin regardless its size.

During rising sea level, coastal drainage basins are flooded by the ocean forming estuaries and then lagoons (OERTEL *et al.*, 1992). The topography of a drainage basin controls the pattern and volume of flooding, as well as the patterns of erosion and accretion during transgression (BELKNAP and KRAFT, 1985). NICHOLS (1989) described how the relationship between rates of sea-level rise and sedimentation produces either deficit or surplus lagoons from coastal basins. Thus, the areal distribution of different elevations (hypsometry) of the pre-transgressed drainage basin can play a major role in the evolution of benthic environments in lagoons. As sea level rises, the initial distribution of benthic environments is inherited from the hypsometric characteristics of the antecedent surface and then modified by transgressive processes.

Table 1. *Percentage of surface area related to the height of solid-material (SM) of the submerged Machipongo River basin.*

Basin Zones	Height above base (m)	Percent of Height	Percent of SM-surface area in zone	Percent of SM-surface area above zone
Gorge	0–12	45	0.03	99
Deep channel	12–21	34	6	94
Upper valley walls	21–24	11	11	89
Interfluve	24–27	10	83	—

Recently, coastal geologists and hydrographers have used hypsographic concepts to study flushing characteristics of coastal lagoons (Boon and Byrne, 1981; Eiser and Kjerfve, 1986; Kjerfve and Magill, 1989; Takeoka, 1984). In this regard, the distribution of solid material (both rock or recent sediments) in a basin area is not as important as the distribution of void space available for inundation by water. The void space represents the capacity of the basin to accommodate air or water, and is a reciprocal of the original Strahler (1952) concept. Boon and Byrne (1981) first modified the Strahler (1952) concept to study tidal inundation in a small tidal-marsh basin. Using a Strahler hypsographic model of Swash Bay (see Table 1 in Boon and Byrne, 1981), the maximum drainage area of the Swash Bay basin occurred above the greatest depth. Thus, the deep channels were associated with the largest surface area of "solid" material, and smallest surface areas of void space. Since Boon and Byrne (1981) were interested in the exchange of water in Swash Bay, they used a reciprocal form (1-h/H) of the Strahler relationship that compared the heights and areas of the void prism. This modified hypsometric relationship provided the concept for developing a geometric framework for partitioning basin prisms into different fractions of land prism (solid), water prism and void (air) prism.

The spatial characteristics of the void space in basins are important parameters controlling the potential flooding of part of the drainage-area prism, and the subsequent development of coastal lagoons. The term *hydro-hypsometry* was introduced (Oertel et al., 2000) to relate fractions of water-surface area at a specific elevation to the fraction of basin height. The *hydro-hypsographic curves* are the inverses of the terrestrial hypsographic curves, in that, the lowest areal percentage occurs at the lowest elevations and the highest areal coverage occurs at the highest elevations. A hydro-hypsographic curve for a coastal lagoon illustrates the incremental change in the submerged land-surface areas at different elevations.

Following the last glacial low-stand, rising sea level inundated land near the edge of the continental shelf forming coastal bays. Throughout the Holocene, transgressive processes drove the bays landward and upward, and finally into place at their present locations (Belknap and Kraft, 1985). The transgressive pathways of the basins were generally determined by the drainage character of the antecedent surface. However, basin dimensions are responses to both the antecedent surface and the transgressive processes acting on the surface. In low sediment-supply areas, basin dimensions are primarily inherited from the antecedent surface. Nichols (1989) described these basins as deficit lagoons. However, some coastal basins have thick columns of sediment covering the antecedent surface. Nichols (1989) described these systems as surplus lagoons.

The Delmarva Peninsula is located on the mid-Atlantic Coastal Plain of the United States. Oertel and Kraft (1994) described the relationships of coastal lagoons in this area to the drainage topography of the antecedent surface. The temporal and spatial location of the coastline during the late Holocene produced a hierarchy of coastal drainage basins. The hierarchal arrangement provided a range of drainage-basin sizes in different orientations and states of geomorphic maturity. Coastal lagoons in the area are coupled to a variety of drainage basins with different antecedent characteristics, and different magnitudes of Holocene sediment fill and scour.

Fisher (1967) described the coastline of the Delmarva Peninsula as a coastal compartment with four landform elements (a headland, two spits and barrier islands). The spits and barrier islands formed an outer coastline offset from the mainland shoreline. Between the inner and outer shorelines, coastal bays and lagoons were associated with the different elements of the coastal compartment (see Oertel and Kraft, 1994). These bays are environmentally rich resources for many benthic and aquatic ecosystems. The environmental quality of these environments is strongly dependent on water depth and exchange of water over different parts of the bay floors. Variations in depth are linked to the complex hypsographic characteristics of antecedent surfaces and sediment accumulation on those surfaces. Very shallow areas provide optimal sites for wetland colonization. Intermediate depths are potentially good sites (optically) for colonization by submerged aquatic vegetation (SAV) but are often subjected to turbulence and resulting turbidity caused by currents and waves.

A series of coastal barrier lagoons occurs along the tide-dominated barrier islands and inlets of the southern Delmarva Peninsula. The lagoons are flooded lowland areas of relatively small drainage basins. The Machipongo River has a small drainage basin that has been partially flooded by the rising Holocene sea. The transgressing sea has driven a coastal barrier lagoon to the distal end of the Machipongo drainage basin. The geographic name of the lagoon is Hog Island Bay and it exchanges tidal water with the coastal ocean through the Great Machipongo Inlet. The discharge of river flow is very small and is well mixed in the lagoon. The mean tidal range is about 1.5 meters. The coastal lagoon is part of the Long-Term Ecological Research (LTER) site for the study of barrier island systems.

METHODS

Remote Sensing Analysis

The total basin area of the lagoon was defined by the mainland boundary at high water, the backbarrier shorelines of Hog Island and Cobb Island and estimated locations of divergent-flow patterns to laterally adjacent lagoons. The total basin area of the lagoon (15,000 ha) including wetlands was estimated using the attributes of a rectified 1993 Landsat TM image. Radiometric values of pixels in Landsat TM images of the Great Machipongo coastal lagoon vary with change in water depth and turbidity. Qualitative inspection of TM images illustrated patterns of radiometric values related to specific benthic environments in the coastal lagoon. Maps of these patterns illustrated a strong relationship between the benthic environments and a submerged drainage basin. By analyzing radiometric values of the TM images in Erdas™, spatial attributes of benthic environments (linked to depth and turbidity) were ascertained. Initially, eight classes of radiometric values were used to categorize different areas of the lagoon (marsh, low marsh, high bars, low bars, shoals, shallow flats, deep flats, and channels). Although the classification was independent of depth or turbidity data, the classes produced spatial groups that were generally related to depth-dependent groups of benthic environments. Maps of the classes provided the spatial patterns of the benthic environments. The spatial attributes of the classes were used to estimate the areas of the benthic environments. Further, the percentage of various benthic environments within the lagoon could be determined and compared for the present elevation of sea level.

Hypsographic and Hydro-hypsographic Analysis

Between 1996–1999 a detailed bathymetric survey of the area was conducted to provide a framework for understanding the benthic and aquatic ecosystems in the coastal lagoon (OERTEL *et al.,* 2000). The fine-scale bathymetric data for the Great Machipongo lagoon permitted an analysis of the physical characteristics of the benthic and aquatic environments in the system. Contour maps of the depth data produced a mosaic of contour ranges with areal attributes. The depth attributes were then related to the benthic environments that were formerly classified by remote sensing techniques.

The Great Machipongo lagoon is an ancient drainage basin modified by the late Holocene transgression. The Holocene sediment carpet over the shallow antecedent surfaces was generally only 1–2 meters thick (OERTEL *et al.,* 1989; OERTEL *et al.,* 1992). The resultant surface has a relief of about 27 meters between the highest and deepest parts of the basin. The "flooded" surface area of the basin is about 15,000 ha. The geomorphic characteristics of the solid-material prism were quantified using hypsographic techniques.

The areal distributions of benthic environments and the attributes of water layers were determined using a hydro-hypsographic concept. Fractions of the total water-surface area were determined from the deepest part of the basin to the surface.

Lastly, the hydrological characteristics of the lagoon were investigated by analyzing the hypsography of water volumes in the basin. Volumes of water were determined for vertically and horizontally partitioned subenvironments in the lagoon.

RESULTS

Hypsographic Analysis

The study area was defined by the boundaries of the coastal lagoon system that drains through the modern Great Machipongo Inlet (Figure 2). The hypsographic curve for this section of the Machipongo River system illustrates the height to surface-area relationships of the "solid-material prism" under the "drainage area." The solid-material prism is composed of Pleistocene and Holocene rocks and sediments. The curve illustrates that the solid-material prism is very large relative to the void prism (Figure 3). Most of the basin surfaces are at a relatively high elevation. The deep elevations in the inlet gorge and submerged channel occupy only a small surface area.

The drainage basin of this section of the ancient Great Machipongo River has been subdivided into four zones (gorge, deep channel, upper valley walls and interfluve). The gorge zone is the deepest part of the basin with depths between 15 and 27 meters (26.75 meters). It is located in the present-day location of the inlet throat. Secondary processes (primarily inlet tidal-scour) scoured the lagoon floor approximately 12 meters deeper than the floor of the ancient river valley (FOYLE, 1994; OERTEL, 1988).

The deep channel zone follows the axis of the ancient Machipongo River. It has elevations 6–15 meters below the interfluve areas of the solid-material prism. The upper valley wall zone is the gently sloping upper section of the valley at elevations 3–6 meters below the interfluve areas. The upper interfluve zone is a gently sloping surface forming an apron around the basin.

The gorge zone spans about 45% of the solid-material height but covers only 0.3% of the surface area of solid material (Figure 3, Table 1). About 99% of the solid-material surface area is above this zone. The deep channel spans an additional 34% of the solid-material height. Although only 21% of the solid-material height occurs at the gorge and deep-channel zones, about 94% of the solid-material surface area is above these zones. Together the gorge and deep-channel zones represent about 79% of the height and only 6% of the surface area.

The upper valley-wall zone spans another 11% of the total height of the solid-material and occupies about 11% of the total area. Thus, 89% of the solid-material surface area is above this zone. The highest interfluve zone represents only 10% of the height, but it occupies about 83% of the surface area.

The hypsometric distribution illustrates that the greatest surface area occurs at the highest elevations of the basins and the greatest relief is confined to the narrow channels. These attributes are generally characteristic of river basins that are well above base level. Since the Machipongo Basin is essentially at base level this relationship is inconsistent with classical paradigms. Either the hypsographic curve of the Great Machipongo basin is a response to fluvial processes that occurred when sea level was at a much lower elevation, or substantial Holocene upbuilding of lagoonal sediments took place at the margins of the submerged ancient river channel. Vibracore and seismic stratigraphic studies of the area show that the thickness of Holocene sedimentation in the interfluve zones was generally 1–2 meters (FOYLE, 1994; OERTEL *et al.,* 1989; OERTEL *et al.,* 1992; OERTEL and KRAFT, 1994). The main backbarrier process influencing the hypsography of the basin was scour in the area of the inlet gorge.

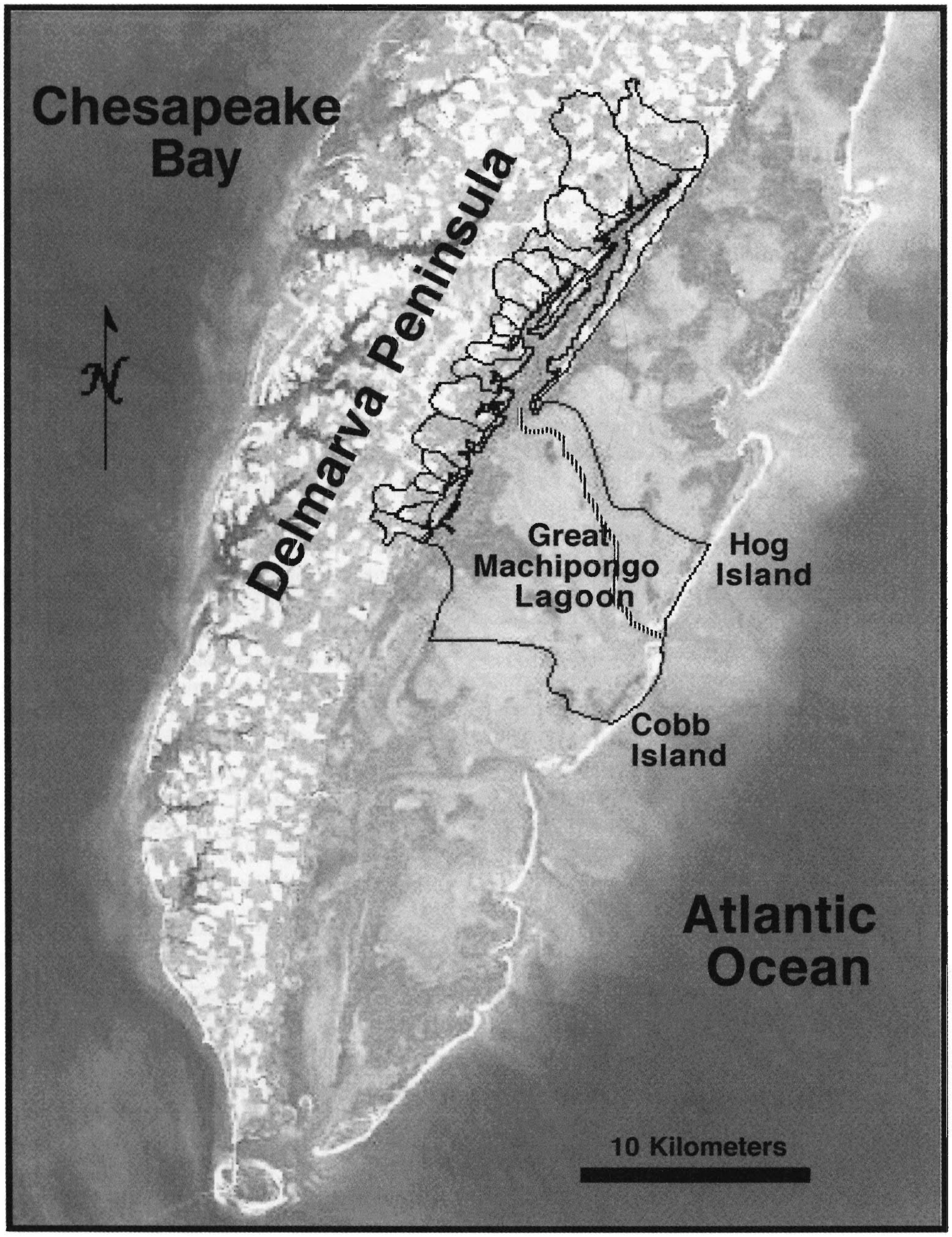

Figure 2. Location map of the Great Machipongo lagoon within the coastal lagoon system of the Delmarva Peninsula. Hatched line is the approximated trace of the submerged channel.

The hypsography of the upper parts of the basin reflect the strong influence of antecedent topography but only weak effects of backbarrier transgressive processes.

Hydro-hypsographic Analysis

Since the basin boundaries were defined by the margins of the coastal lagoon, all of the void prism is occupied by water at high tide. The zones in the lagoon were classified by remote sensing attributes and environmental characteristics. A modified hypsometric technique was used to analyze the distribution of the water prism (the flooded void prism). The "modified" hypsographic curves (hydro-hypsographic curves) have a reciprocal relationship with hypsographic curves. Hydro-hypsographic analysis of the Great Machipongo basin was used to describe the relationship between water depth and the related surface areas of benthic environments.

Depth is a major factor governing the spatial distribution

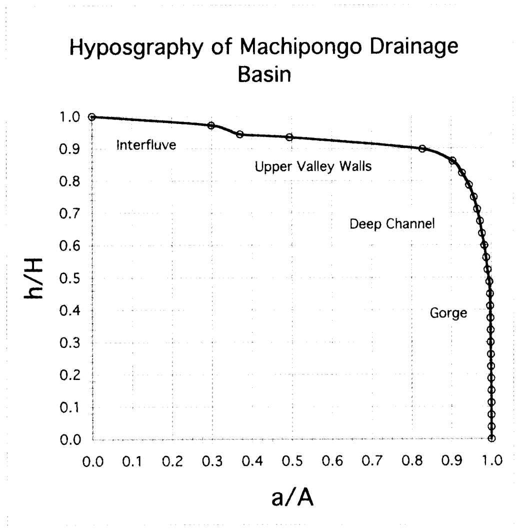

Figure 3. Hypsographic curve of the Machipongo River lagoon. Axis labels refer to dimensions shown in Fig. 1.

of benthic environments of coastal lagoons. The hydro-hypsometric curve of the Great Machipongo lagoon, illustrates the relationships between depth and available surface areas for benthic community development (Table 2, Figure 4). The greatest depths in the lagoon occurred in the inlet-throat section, where a gorge was surveyed with depths greater than −26 meters (msl datum). The hydro-hypsographic curve for the Great Machipongo lagoon illustrated the spatial distribution of six benthic environments (at the present sea level). The upper intertidal surfaces were colonized by marshes. The marsh, while representing only 3% of the total depth of the lagoon, occupied 30% of the benthic surface of the basin. The intertidal flats also represented 3% of the basin depth, but occupied only 7% of the benthic surface area.

During windy events, the shallow subtidal surfaces were intermittently churned by lagoonal waves that also mixed the shallow water column. During calm intervals, shallow surfaces had properties favorable for plant communities. By late summer, portions of the subtidal flats were colonized by macrophyte communities. The shallow subtidal flats occupied about 46% of the lagoonal surface. These three environments (marsh, intertidal and subtidal flats) covered about 83% of the benthic surface area of the lagoon, but represented only 11% of the lagoonal depth.

The deep flats added another 8% of the lagoon surface to the prospective benthic ecosystem. The deep flats were generally below the wave base of the smaller lagoonal waves but were stirred by tidal currents and occasionally larger waves. Some benthic surfaces of the shallow and deep flats may be favorable for SAV recolonization.

The deep and shallow channels represented only about 9% of the surface area, but about 86% of the lagoonal depth. The channels were conduits for swift ebbing and flooding currents that flushed the system, making a well-mixed water column above the benthic communities.

Table 2. *Percentage of water-column height and surface area at six benthic environments in the Great Machipongo lagoon.*

Benthic Zones	Depth (m)	Percent of Water Column Height	Percent of Benthic Surface Area
Marsh	0.75 to msl	3	30
Intertidal Flats	msl to mlw	3	7
Shallow Flats	mlw to −2	5	46
Deep Flats	−2 to −3	4	8
Shallow Channels	−3 to −6	11	5
Deep Channels	−6 to −25	75	4

Hydrological Analysis

Integration of water layers in the lagoon produced a total water prism (Ω_{tot}) in the basin of about 3.13×10^8 cubic meters. Most of the lagoon water was over shallow flats where depths were less than 2 meters. An average hydraulic depth of 2.1 meters for the lagoon was estimated by dividing the tidal prism by the surface area of the lagoon (15,085 ha).

Integration of the upper 1.5 meters of the water surface produced a tidal prism (Ω_{tide}) of 1.7×10^8 cubic meters. At high tide the tidal prism represented about 54% of the volume of water in the Great Machipongo Lagoon.

A graph of the fraction of the water-column height to the fractions of basin volume (volume hypsographic curve) was used to illustrate the distribution of water within the basin (Figure 5). The *volume-hypsographic curve* illustrated that about 76% of the water volume was located in the upper 10% of the basin height. If water were completely mixed before leaving and entering the inlet, then the hydraulic turn-over time would be about two tidal cycles. Hydraulic flushing of the lagoon with the coastal ocean is very good. It is suggested

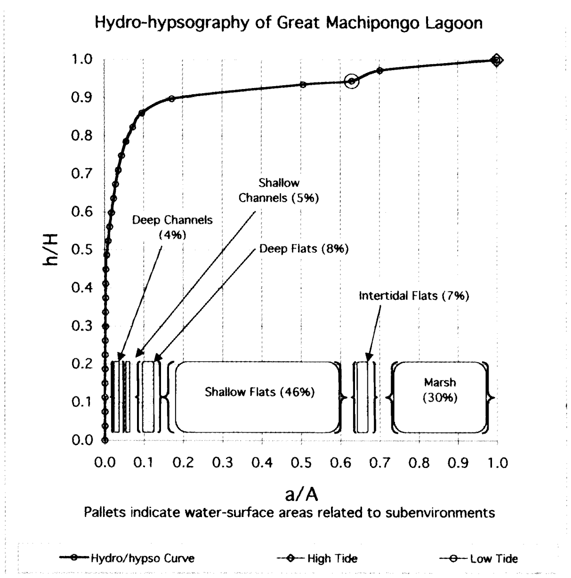

Figure 4. Hydro-hypsographic curve of the Great Machipongo lagoon. Axis labels refer to dimensions shown in Fig. 1.

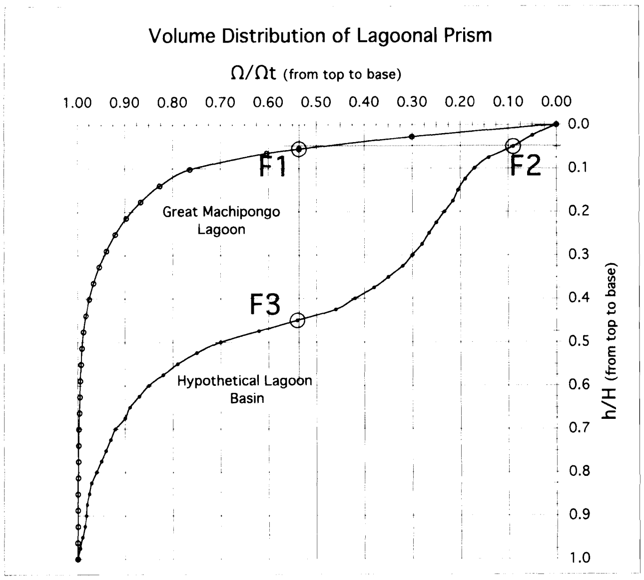

Figure 5. Volume-hypsographic curve of the Great Machipongo lagoon and a hypothetical lagoon. On the volume-hypsographic curve for the Great Machipongo lagoon, the F-point (*F1*) illustrates that the tidal prism is only 6% of the water column thickness but about 54% of the total water prism. On the curve for the hypothetical lagoon, the F-point (*F2*) represents only 6% of the water column thickness, and the tidal prism is only about 9% of the total water prism. If the F-point (*F3*) represented only 54% of the total water prism, then the tidal range would have to represent about 45% of then total water column.

that lagoons with similar volume-hypsographic curves are well flushed.

Distribution of Water Over Benthic Environments

Since water volume in a lagoon is an attribute determined by depth and surface area, hydro-hypsography is a major factor controlling the volume of water above the lagoon floor. The water associated with specific benthic and aquatic subenvironments in the lagoon (marshes, intertidal flats, shallow flats, deep flats, shallow channels and deep channels) was of specific interest to this study. Lagoonal water was partitioned into six prisms associated with these zones (Table 3). Table 3 illustrates the percentages of the lagoon prism (3.13×10^8 cubic meters of water) that were vertically partitioned over the six benthic environments.

The largest volume of water in the lagoon (45%) was over the *shallow tidal flats*. This is primarily due to the large surface area of the shallow tidal flats described above. The *intertidal-flats* had the smallest volume of water (4%) above it. This was primarily due to the small surface area of the zone combined with the shallow intertidal depths. Although the marshes occupied 30% of the surface area of the lagoon floor (see above), the very thin water column produced a volume that was only 5% of the total basin prism. Together, the marshes and intertidal flats represented only 9% of the lagoonal prism. However, since both environments are intertidal 100% of the water is "turned-over" with each tidal cycle. The concept of hydraulic turn-over as it applies to specific environments within the lagoon does not require exit from the lagoon system. In this use, hydraulic turn-over refers to the exchange of water over the environment with mixed water from other parts of the lagoon. When the water volumes above the shallow flats, intertidal flats, and marshes are all considered, they represented 54% of the water in the Great Machipongo lagoon system.

The cumulative volume of water between the deep flats and high water-elevation accounted for about 66% of the entire basin. Hydraulic turn-over time was less than two tidal cycles for the water over the marshes and flats. Although the channels (shallow and deep channels) occupied only about 9% of the basin surface (Table 2), the volume of water over these environments accounted for about 34% of the total water prism in the lagoon (Table 3).

Distribution of *Tidal* Water Over Benthic Environments

Table 3 also illustrates the percentages of the tidal prism (1.7×10^8 cubic meters of water) located in six subenvironments of the Great Machipongo Lagoon. Volumes were based on the 1.5- meter tidal range combined with the surface areas of each of the six subenvironments. The largest percentage (60%) of the tidal prism occurred over the shallow tidal flats. The marshes and deep flats accounted for the second largest amounts of tidal water at 10% each. About 87% of the lagoonal tidal prism occurred over the shallow environments that were less than 3 meters deep. The remaining 13% of the tidal prism was over the narrow channel environments (shallow and deep channels).

Horizontally Stratified Hydrologic Characteristics

The water in the Great Machipongo lagoon can be partitioned in horizontal layers without reference to benthic zones

Table 3. *Relative volume of water in six prisms located above benthic subenvironments of the Great Machipongo lagoon.*

Benthic Zones	Depth Ranges (m)	Percent of Basin Prism	Percent of Tidal Prism	Percent tidal height to water column at zone	Hydraulic Turn-over Time (in tidal cycles)
Marsh	0.75 to 0.0	5	10	100	1
Intertidal Flats	0.0 to −0.75	4	7	100	1
Shallow Flats	−0.75 to −2.0	45	60	72	1.4
Deep Flats	−2.0 to −3.0	12	10	46	2.2
Shallow Channels	−3.0 to −6.0	12	7	30	3.3
Deep Channels	−6.0 to −26.75	22	6	14	7.1

Table 4. *Relative volume of water in six horizontally stratified wafers.*

Wafer Designation	Depth Range (m)	Percent of Total Basin Prism	Hydraulic Turn-over Time (tidal cycles)
1	0.75 to 0.0	30	1
2	0.0 to −0.75	24	1
3	−0.75 to −2.0	23	1.4
4	−2.0 to −3.0	6	1.5
5	−3.0 to −6.0	9	1.7
6	−6.0 to −26.75	8	1.9

(Table 4). This stratified analysis of the lagoonal prism was used to describe the aquatic systems that are water-depth dependent. Six depth layers (wafers) were analyzed. The wafers of water had the same depth ranges as the six subenvironments but their lateral extent was based on the areas of hypsographic layers rather than being limited by the areas of the sub environments (Figure 5). Table 4 illustrates the hydrologic characteristics of these aquatic wafers.

The hydro-hypsography of the Great Machipongo lagoon has an important influence on the distribution of water in the basin. Approximately 54% of the water in the lagoon was in the upper 1.5 meters (the tidal range). That is, only a fluctuation of 5.5 % of the surface-water elevation could produce a 54% change in water volume in the basin. Seventy-six percent of the water in the lagoon occurred in the upper 2 meters of the basin. Whereas, only 8% of the water in the lagoon occurred at depths greater than 6 meters (msl-datum).

DISCUSSION AND CONCLUSIONS

Since 54% of the water in the Great Machipongo lagoon is exchanged with each tidal cycle, it is suggested that the shape of the volume-hypsographic curve is typical of other well-flushed lagoons. The x-axis of a volume-hypsographic curve is the ratio of the volume of a water lens to the total prism of the basin ($\Omega_{\text{lens}}/\Omega_{\text{total}}$). The tidal prism is a very specific lens at the top of the water column. Thus, flushing characteristics are dependent on the shape of the curve that determines the relative volumes of the tidal prism and the total lagoon prism.

Since, the position of the tidal lens on a volume-hypsographic curve is so critical to flushing, it is defined here as the flushing point (F-point). The F-point of any basin describes the fraction of water in a coastal lagoon exchanged with each tidal cycle (Equation 1).

$$F = \frac{\Omega_{\text{tidal prism}}}{\Omega_{\text{total prism}}} \tag{1}$$

In well-mixed water bodies, hydraulic turn-over time (HTT) is the time that it takes to replace the total prism by tidal exchanges ($\Omega_{\text{total}}/\Omega_{\text{tidal prism}}$). Therefore, *F* is inversely related to hydraulic turn-over (HT).

$$HT = \frac{\Omega_{\text{total prism}}}{\Omega_{\text{tidal prism}}} = \frac{1}{F} \tag{2}$$

For the Great Machipongo coastal lagoon, HTT is about 1.85 tidal cycles. This rapid flushing characteristic is closely dependent on the shape of the hypsographic curve for the Machipongo system. To illustrate this, a comparison of turn-over time was made with a hypothetical basin with a different hypsographic curve (Figure 5). The tidal range of the Great Machipongo lagoon represents only about 6% of the total depth of the lagoon (Table 2). However, the distribution of water (shape of the volume-hypsographic curve), results in a F-value of .54 (point *F1* Figure 5) which yields a hydraulic turn-over of 1.85 or a hydraulic turn-over time of 1.85 tidal cycles.

If the tidal range of the hypothetical system were the same fraction of the basin depth (point *F2*), then the F-value would be only .09, and the resulting hydraulic turn-over time would be about 11 tidal cycles. The curve of the hypothetical basin also illustrates (see point *F3,* Figure 5) that for a F-value of .54, the tidal range would have to be about 45% of the basin depth. Thus, volume-hypsographic curves that are convexed toward the bottom-right corner of a graph tend to have poorer flushing properties, unless most of the basin height is depleted at low tide.

On a volume-hypsographic curve, F-point is located at the elevation of low tide. Movement of the F-point to the right along the curve, increases the hydraulic turn-over time and inhibits flushing in a coastal lagoon. Conversely, when this point moves to the left along the curve, flushing is enhanced in the coastal lagoon. An increase in tidal range or a decrease in basin volume causes the F-point to shift to the left. Decreases in tidal range or increases in basin volume shift the F-point to the right. A comparison of these two curves illustrates the power of using hypsographic curves to understand flushing of coastal lagoons.

Along the mid-Atlantic region of the United States, there are many coastal lagoons with similar surface areas. Because of similarities in size, it might be assumed that these lagoons would have similar flushing characteristics. However, the bathymetry below the surface might be quite different producing different volume-hypsographies. Flushing is associated with the relationship between F-value and volume-hypsography and *not* basin size. Although two basins may have similar surface areas, the hydro-hypsometric characteristics of their void prisms may be quite different. Basins with different bathymetry can be organized into a suite of volume-hypsographic curves ranging from convexed upward to downward (Figure 6). Each curve has the potential to produce significantly different flushing characteristics. On curve *A* of Figure 6, if the tidal prism were located in the upper 5% of the water column, then it would exchange 50% of the water and would be "well" flushed." Curve F (Figure 6) would be poorly flushed if the tidal prism were located in the upper 5% of the water column. To exchange 50% of the basin in Curve F, the tidal prism would have to drain 90% of the basin depth. Thus, the hydro-hypsometrics of coastal lagoons can be used to create volume-hypsographs that are much better indicators of flushing than surface area.

Hypsometric techniques may also have application in studying transgressive processes. At large temporal scales, sea-level rise affects the inundation characteristics of coastal basins. Today the tidal flats of the Great Machipongo lagoon

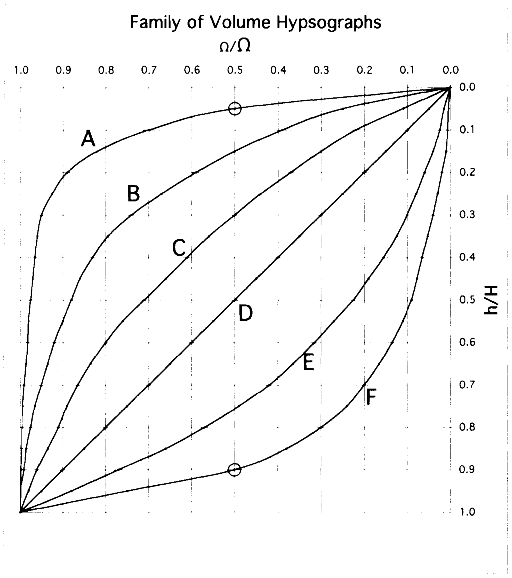

Figure 6. Suite of hypothetical volume-hypsographic curves showing the relationship of relative prisms of water at different horizons of a basin. The circles indicate the relative depths above which 50% of the water volume occurs in the basin. On curve A, 50% of the water volume occurs within the upper 5% of the distance from the surface to the bottom. On curve F, 50% of the water volume occurs at a depth of 90% of the distance from the surface to the bottom.

represent greater than 50% of the benthic environment. The basin configuration was considerably different when sea level was lower. The shape of the basin floor is the resultant of inundation of the antecedent basin combined with backbarrier processes of erosion and accretion. Hydro-hypsographic analysis of the ancient drainage basin involves knowing the 3-dimensional shape of the basin prior to transgressive modification. Previous investigations of the Machipongo tidal flats found that surface was underlain by a thin carpet of Holocene sediment above the antecedent surface (OERTEL *et al.,* 1989; OERTEL *et al.,* 1992; OERTEL and KRAFT, 1994). By constructing a hydro-hypsographic curve of the antecedent surface the distribution of marshes related to the transgressed surface could be determined for previous elevations of sea level. If the shape of the hypsographic curves for antecedent and modern basins were similar, then marshes of the Great Machipongo lagoon would have been considerably more extensive just 500–1,000 years ago. When analyzing the decline in marsh area between 500 YBP and the present, hypsometric relationships must be considered, *not* just recent anthropogenic stresses.

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