EVALUATION OF EROSIONAL FORCINGS OF A BEACH/BERM/WETLAND SYSTEM AND APPLICABLE RESTORATION TECHNOLOGIES

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ABSTRACT

The purpose of this study was to evaluate the local and regional processes causing the shoreline recession of an eroding beach/berm/wetland system on the eastern shore of Mobile Bay. The analysis was then used to evaluate different technologies which could meld to create a holistic shoreline protection design to fortify the entire spectrum of the shoreline. Wind waves are the major erosional force causing a bi-directional, but southerly dominated, longshore transport and an erosional cross-shore transport during large wave events. Erosion mitigation technologies which promote ecological integrity are presented and include: oyster shell breakwaters, SAV establishment, intertidal grass plantings, and tree and shrub plantings. By combining these technologies, a plan which mitigates erosion as well as greatly increases the health of the local ecosystem can be formed. By fortifying in this manner the shoreline and its communities can be more resilient and prepared for future climatological changes and conditions.

PREFACE

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Dr. David Shaw is Director of the NGI and Dr. Michael Carron is Co-Director and Chief Scientific Officer. The NGI web site is at http://www.northerngulfinstitute.org/home/ngi.php

TABLE OF CONTENTS

CHAPTER

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Like many estuaries around the world, Mobile Bay has a large and ever-growing human population living about its shorelines and surrounding watersheds. These people are concerned about living resources and aquatic health of the bays and waterways as well as land loss due to erosion. Shoreline erosion adversely affects the health of estuarine systems by increasing sediment suspension and decreasing light availability for benthic organisms and submerged aquatic vegetation. The proliferation of shoreline armament attests that shoreline retreat has been a topic of concern in Mobile Bay for some time. It was estimated that between 1955 and 1997 shoreline armoring, typically bulkheading, was increased from 5 percent to 30 percent of the 100 hundred mile urban estuarine shoreline (Douglass, 1999). This type of hard structure has been shown to be an ineffective manner of shoreline protection as it only addresses the symptoms and not the actual causes of the erosion. Thus erosion problems and sediment deficits are passed along down the coastline.

These problems highlight the need for research into sediment-process aware and ecologically minded solutions to shoreline erosion problems that act at the cause, instead of the consequences, of the sediment deficit problem. The United States Fish and Wildlife Service and the Mobile Bay National Estuary Program have addressed shoreline retreat in Mobile Bay by implementing and encouraging shoreline and habitat restoration projects in the bay to promote healthy coastal ecosystems. In order to give restoration projects the best chance of succeeding, a thorough investigation of the sedimentological forcings which are causing the shoreline erosion must be performed.

1.1 Purpose

The purpose of this study is to evaluate the local and regional processes causing the shoreline recession of an eroding beach/berm/wetland system on the eastern shore of Mobile Bay and to evaluate different technologies which could meld to create a holistic shoreline protection design for the study area.

CHAPTER 2

GENERAL DESCRIPTION

The beach/berm/wetland system is located in the Northern Gulf of Mexico, along the southeastern shore of Mobile Bay, as is presented in Figure 2.1. Mobile Bay is a drowned river valley that acts as the receiving waters of the sixth largest river basin in the United States. The Bay is approximately fifty (50) km long from the mouth of the Mobile-Tensaw Delta to the Bay inlet between the eastern end of Dauphin Island and the western end of the Fort Morgan Peninsula. Mobile Bay's widest point comes between the Mississippi Sound and Bon Secour Bay and measures about 37 km (Stout, 1998).

Mobile Bay has an average depth from 3-4 m with a mean tidal range of 0.4 m and a maximum spring tide of around 0.8 m with a minimum neap tide near zero. There are dredged channels running north to south and east to west through the bay. The longitudinal channel, which acts as the access channel to the Port of Mobile, is located at 88° 01' W and is maintained at about twenty meters deep. The latitudinal channel is 12 feet deep and is used as part of the Gulf Intercoastal Waterway. Mobile Bay receives fresh water from local stream flow and sheet flow into the bay but the majority of the freshwater input is from one the larger watersheds in North America, the Mobile Watershed.

The climate around Mobile is humid and subtropical. The summers are hot with frequent afternoon thunderstorms, while the winters are mild with some cold and windy winter storms. The winds in the area generally have low mean magnitude of less than 5 m/s but during the winter months weather fronts moving through the area can produce winds speeds of 10 to 15 m/s (Schroeder et. al, 1990). Hurricanes and tropical storms also frequent the area and can cause morphological changes to the embayment and its shorelines.

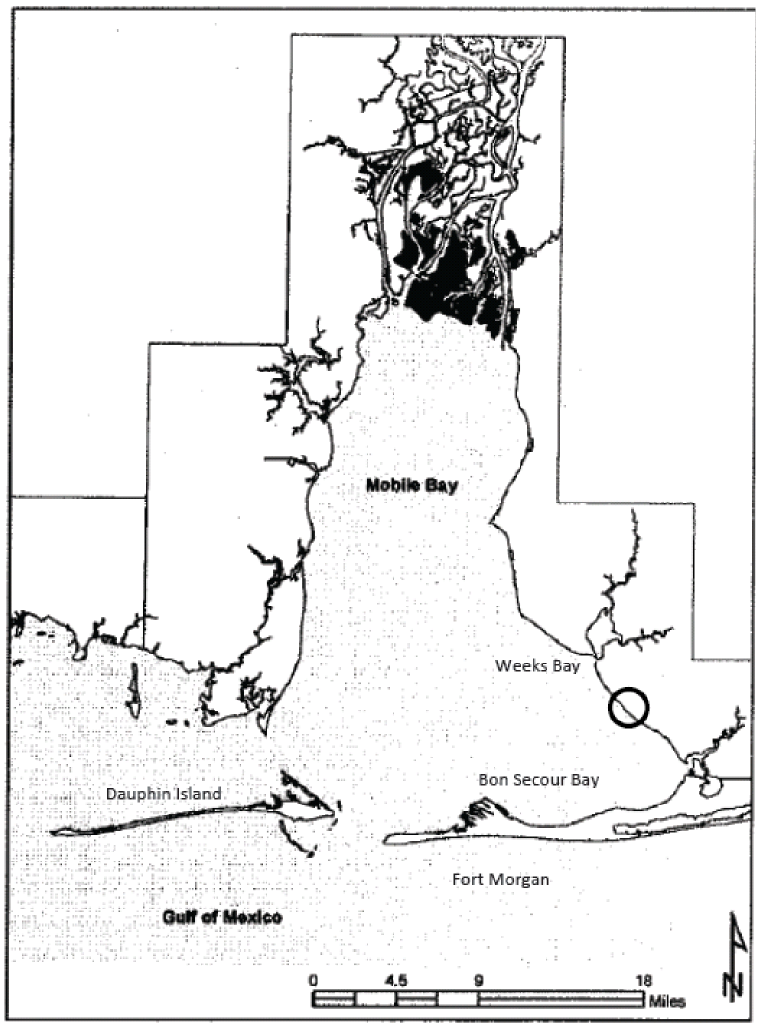

Figure 2.1 Mobile Bay with Study Area Circled

The shoreline and landward area to be studied are managed by the Weeks Bay National Estuarine Research Reserve (WBNERR) and is referred to as the 'Swift Tract.' The study area begins about 4.2 km southeast from the Weeks Bay Inlet southward towards Bon Secour Bay. The shoreline of interest in this study is about 1 km long. The shoreline is heavily fortified with Cypress stumps and debris, which are usually below the water surface but during extreme low water levels can be seen above the water surface. The swash zone is fairly steep with sand being the dominant soil type. The beach runs up to a berm which is the separation between Mobile Bay and ephemeral freshwater wetland. The berm and seaward beach have spotted growth of *Spartina patens*, also known as Marsh Hay and Salt Meadow Cordgrass. Located and protected behind the berm is a freshwater wetland which is supporting diverse populations of flora and fauna. The wetland also contributes to increased water quality in the bay by filtering sheet flow before entering the system. The open wetland is present for around 100 meters landward of the shoreline. Behind the freshwater wetland is an area of forested wetland and slash pines. The area is not easily accessible by traditional automobiles.

Figure 2.2 Aerial Photo of Study Area (http://dl.nwrc.gov/mb/diglibdetails.asp?UNIQUEID=276&type=aerial accessed: 28.Jan.08)

The berm also perches the wetland above sea level, which causes freshwater to seep through the porous medium of the berm and beach. This can be witnessed by the dark water and beaches which are stained with tannins picked up by the freshwater as it filters through the wetland and its decaying organic matter. In some cases of high water levels in the wetland gurgling brooks of tea-stained water emerge through the berm and run into the Bay as can be seen in Figure 2.3.

Figure 2.3 Tannin stained water rushing through a section of berm. (Author's Photo)

The shoreline is oriented in a NNW to SSE direction and therefore the full fetch of Mobile Bay acts perpendicularly to the study area. Clearly the shoreline in this area has been receding for some time as witnessed by the proliferation of stumps just below the swash zone and the presence of stumps as far out as 75 m from the current shoreline. These stumps were at one time located either in a wetland or atop the berm before a variety of factors caused the shoreline to migrate landward.

Figure 2.4 Study Area Shoreline with Cypress Stump Armament (Author's Photo, 30.Nov.07)

Along with uniform coastline recession, the shoreline is affected by the erosional undercutting of the root mat in some areas of the coast where healthy *Spartina patens* growth is located. This type of erosion occurs when the fringe wetland succeed and begin to thrive. The plants begin accumulating sediment and organic material and the elevation of the root mat increases. The problem then occurs in the area of the swashzone which is too deep the grasses to survive. This area remains at the same elevation and the place where the grass area meets the uncolonize bottom a vertical face will occur. This vertical face has little protection and is very vulnerable to erosion. This scarp erosion will occur and the vertical face will be eroded by wave action and the fringe wetland will be undermined and destroyed. Figures 2.4 and 2.5 illustrate this concept and its presence on the shoreline of interest.

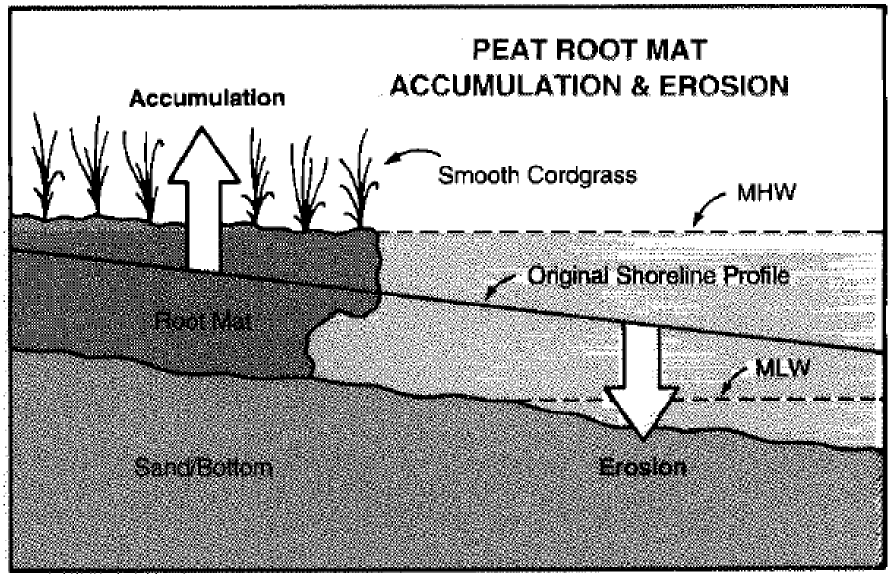

Figure 2.5 Fringe wetland undermining (Broome, et. al, 1992)

Figure 2.6 Fringe wetland undermining at project shoreline (Author's Photo)

It is clear that a variety of forces are causing this beach/berm/wetland system to erode and these forces must be delineated. Local and regional processes must be identified and critiqued to determine which forcings are controlling the shoreline recession. Some possible processes which are contributing to the erosion include: wind waves, ship waves, longshore transport of sediment, shoreline armament around the bay, and major episodic events such as hurricanes and winter storms.

CHAPTER 3

ANALYSIS OF LOCAL AND REGIONAL PROCESSES

3.1 Field Data Collection

Several trips to the study area were made during the study period. These trips were for data collection of all kinds. An idea of the processes and the layout of the study area were essential to understand in order to be able to develop a design which fits into the current system. It was also necessary to take sediment samples and get an idea of the erosional processes present in and adjacent to the site. Some trips were made with personnel from the Weeks Bay National Estuarine Research Reserve (WBNERR) and Dauphin Island Sea Lab (DISL) and another was made solo in a kayak. The solo trip was done in a kayak to be able to more easily move close to the shore along the site as well as north and south of the study area. This was very helpful as it allowed close inspection of the natural shoreline protection systems in the immediate area.

The most important tangible result derived from the field trips was sediment samples from the site. Sediment sample were taken from the top of the berm to nearly 100 feet out into the bay. These samples were taken back to the lab, dried, and a sieve analysis was performed. The grain size distribution charts for each sample and there locations can be found in the Appendix. A representative grain size of 0.45 millimeters (mm) was determined for the beach and this was used to determine the fall velocity and therefore the cross-shore transport.

Figure 3.1 Sampling Vessel and Equipment at Study Area

Another thing which was learned first hand during sediment sampling was about the slope of the beach out in the bay. The slope is very low and therefore water depth does not increase very rapidly. This was shown in NOAA nautical charts but it is always better to confirm and ground-truth when possible.

General observation of the study area was another important component of the field trip. A lot can be determined by simple observation of the area and its adjacent lands. One of the first questions to be asked was, of course, “Is this beach actively eroding?” The answer was clearly yes as can be seen in the following photos.

Figure 3.2 Erosion at Study Area

Figure 3.3 View of Study Area from North

The preceding photos definitely show a beach system which is erosional. Figure 3.2 shows considerable scarp erosion as caused by undercutting of the root bed, but it also shows a young healthy stands of *Spartina patens* along the waters edge. This is a very encouraging sign for survivability of a shoreline plantings type of erosion control. The scarp erosion indicates that something must be done to protect the toe of the root mat from erosion. This can be accomplished by fortifying the foot with oyster shells or by submerged aquatic or emergent vegetation growing just seaward of the root mat, as seems to be occurring presently. The picture in figure 3.3 is also connotative of an eroding beach with a headland. From this view from the North, it is possible to see the beginnings of the cuspate type beach formation. This beach formation is typical of the coastlines all over the world. But this trend toward a cuspate beach is probably temporary as the headland which is causing this formation is not a rocky outcrop, as is usually seen on the West Coast of the United States, but an area of slightly higher ground with some larger trees still prevalent in the area. Without protection, this headland is temporary and when it fails to the shoreline will work towards a new equilibrium.

When looking at differences between the erosional study area and other areas close by, one of the most striking differences that is noticed is that the study area has a lack of trees along the shore and landward. Most other areas close by which do not seem to be eroding as quickly have a prevalence of trees along the shore and landward. In some places the trees are even dead but their continued presence still helps to preserve the area in which they stand. This suggests that the trees play a vital role in giving the shoreline an underlying framework of structural integrity during high wave and water situations.

An idea of longshore transport can be obtained by looking a small pocket beaches as well as area groins have been built north of the study area. Figures 3.4, 3.5, and 3.6 show that longshore transport around June 16th 2008 was primarily toward the northerly direction along the beach. It can be seen that there is a build up on the northern side of all pocket beaches and the southern side of the groins around the study area. This is interesting judging from the shape of the beach. The way that the log spiral form is aligned seems to suggest that the majority of the transport occurs toward the southerly direction. This is probably true at other times of year, but not during the summer. The seasonal changes in weather patterns most likely cause a seasonal change in longshore transport direction. The longshore transport rose also shows that the longshore transport in the area is bidirectional, thereby helping to validate the hypothesis of a seasonal variable longshore transport system.

Figure 3.4 Bulkhead and Groin System ~3.5 km North of Study Area

Figure 3.5 Pocket Beach ~1km North of Study Area

Figure 3.6 Groin and Bulkhead System by Mouth of Weeks Bay (~4km North of Study Area)

All of three of these pictures clearly show that longshore transport at the current time is toward the northerly direction along the shoreline. The piles of sand on the southerly side of the groins are clear indications of northerly longshore transport. This is essential information when designing a coastal erosion project as it is of utmost importance not to pass along problems or increase the severity of erosion issues in the surrounding area. Therefore erosion control plans must be cognizant of any fluctuations to the sediment budget that the plan may cause.

Another important component of gathering field data is getting to know what is present in the environment of the study area. The flora of an area is essential in coastal erosion projects which could involve plantings in the erosion remediation plan. An encouraging sign was the presence of shoreline grasses which are commonly recognized and planted to protect shorelines, including both *Spartina patens* and *Spartina alterniflora*.

Figure 3.7 Pocket Beach Just South of Study Area

Figure 3.8 View of Intermittent Wetland

The previous two pictures show commonly occurring coastal grasses in the Southeastern United States. Figure 3.7 shows a pocket beach just south of the boundary of the study area. Just a few of plants pictured are *Spartina alterniflora, Spartina patens, Juncus roemerianus,* and *Phragmites australis*, whose common names are smooth cordgrass, salt meadow cordgrass, black needlerush, and the common reed, respectively. The smooth cordgrass is growing in the tidal zone, the salt meadow cordgrass in growing in the upper tidal zone, the black needlerush is growing above high tide, and *Phragmites* is growing from high tide to the back side of the berm. Figure 3.8 is a view of the intermittent wetland which the beach/berm system is protecting and keeping perched above the bay for parts of the year. The main grass in the picture with brown tops is *Cladium Jamaicense*, or commonly called saw grass. It is a sedge and is the characteristic plant of the Florida Everglades (Tiner, 1993). There is a very healthy population of saw grass behind the berm.

This coastal line has an abundance of plant life some of which is quite aesthetically appealing. This is also encouraging because if a shoreline protection plan can inhibit erosion, use local materials, improve natural ecosystem function, be cost-efficient, and be attractive, then these ideas should be appealing to environmentally and aesthetically aware homeowners and landowners. And if this technology is used by private citizens then it will proliferate much more quickly than if it was dependant upon university studies and government agencies. Some examples of attractive plants found in and around the study area are presented below. These plants could be used as accents to shoreline protection plan that will be highly visible. This refinement is not necessary for the shoreline project to be successful but this idea was still be explored because of the possibility that this technology could be used in more visible public places or private homes and property.

Figure 3.9 Aesthetically Appealing Flora of the Study Area

The previous compilation of photos was taken by the author in very close proximity to the study area. The top two pictures are Morning Glories. The purple one being a Salt Marsh Morning Glory or *Ipomoea sagittata*, and the white one being a Beach Morning Glory or *Ipomoea stolonifera*. The large white flower with a deep red center, located in the middle row in the left column is the Rose Mallow or *Hibiscus moscheutos*. The yellow flower is called a Sea Oxeye, *Borrichia frutescens*. The other two photos on the bottom are of common marsh flora, where the one on the right is the easily recognized a Cattail species either *Typha latifolia*, the Broad-leaved Cattail, or *Typha domingensis*, the Southern Cattail. Ralph Tiner's *Field Guide to Coastal Wetland Plants of the Southeastern United States* was used for identification and scientific names of the trees, shrubs, and flowering plants (Tiner and Rorer, 1993).

3.2 Wave Climate

Several different factors are probably encouraging shoreline retreat on the beach/berm/wetland system. One of the most formative forces acting on the study area is wave energy impacting the shoreline. This wave energy is mostly derived from winds which move over the water and translate some energy to the water. This wind energy is manifest in the waters of Mobile Bay as waves. Wave characteristics like wave height, period, wave length can be measured, accumulated, or estimated and is referred to as the wave climate. "Wave climate is influenced by fetch (the distance over which the wind blows to generate waves), wind direction and speed, offshore and nearshore depths, nearshore bottom slope, shoreline orientation, and distance from navigation channels" (Roland and Douglass, 2005).

Wave climate in the study area was determined by following the methodology set out in Roland and Douglass (2005). A wind-wave hindcast was performed from historical wind data by using a modified form of the Hasselmann equations, which are used in the U.S. Army Corps of Engineers (USACE) 1984 Shoreline Protection Manual (SPM) and its successor the Coastal Engineering Manual. The Hasselmann equation is an empirical formulation to estimate shallow-water wave height. The driving variables which determine wave height from the equation are fetch, average depth over the fetch, and wind speed.

Hourly wind speeds from 1987 to 2007 were obtained from the National Data Buoy Center of NOAA from Station DPIA1-Dauphin Island. The buoy is located on the eastern end of Dauphin Island by the Dauphin Island Sea Lab at 30˚ 14' 54" N, 88˚04'24" W. The anemometer is placed 13.5 meters above mean sea level and averages wind readings over a 2 minutes period. Wind data from the twenty one years of record was tabulated and sorted. First the winds were broken into directional groups of 10˚ degrees, such as 0-9˚, 10-19˚, 20-29˚, etc. These directional groups were then broken into 1 meter per second velocity groups. Velocities were recorded with significant digits in the tenth of a meter per second range and were rounded to the closest whole number and were tabulated as such. For example, records of wind speeds from 0.5 m/s to 1.4 m/s were tabulated as 1 m/s wind speeds and records of 1.5 m/s to 2.4 m/s were tabulated as 2 m/s and so on and so forth. After these groups were delineated, a frequency analysis of wind conditions in the area was performed. In following with the Roland and Douglass (2005), wind roses were then constructed for all the winds of record and the top 20 percent of wind speeds. The high speed wind rose represents winds that are equal to or above 8 meters per second (m/s), or 18 miles per hour (mph) and represents winds which are in the 80 percentile or higher, as was done in Roland and Douglass (2005).

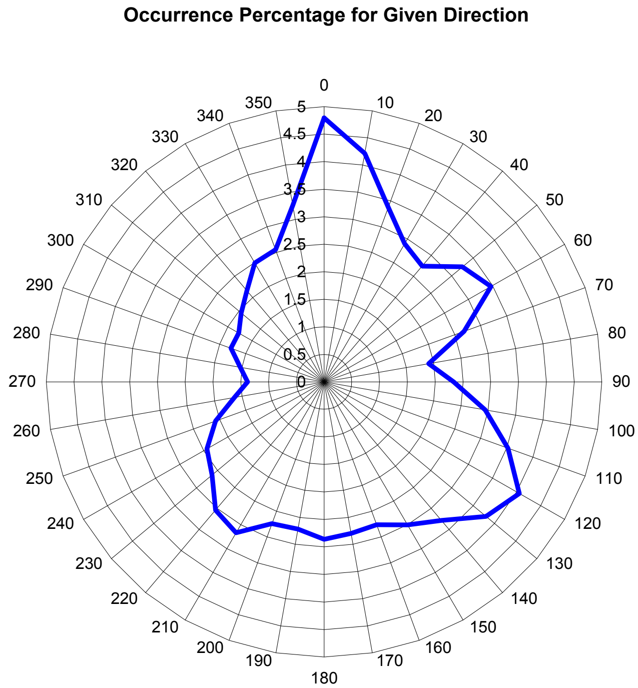

Figure 3.10 All Winds Rose

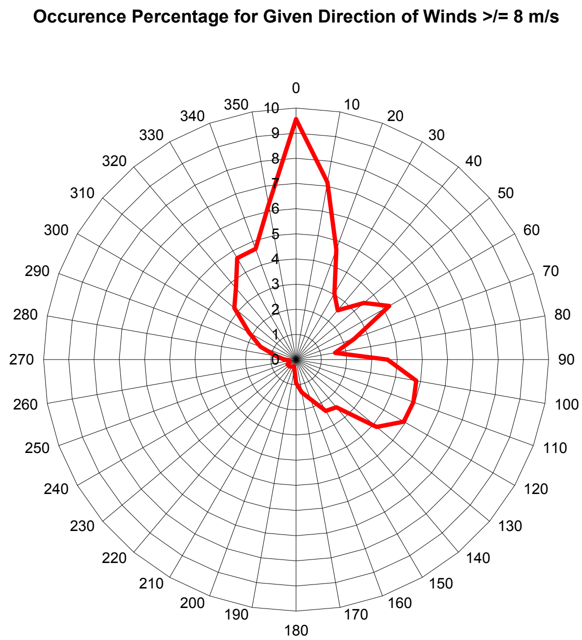

Figure 3.11 High Winds Rose

The next factors influencing wave climate to be gathered were the fetch and average depth across the fetch. The Mobile Bay NOAA Bathymetric Chart 11376 was used to determine these attributes for each 10˚ degree segment radiating outward from the study area. Depth estimations were also aided by separate work the author has been doing, in which many water quality measurements are taken and depths recorded around Mobile Bay. Estimations were also validated by local experts.

Table 3.1 Fetches and Depths along Fetch

Directional Segment	Average Fetch (Nm)	Average Fetch (Feet)	Depth (Feet)
0-9	0	0	NA
10-19	0	0	NA
20-29	0	0	NA
30-39	0	0	NA
40-49	0	0	NA
50-59	0	0	NA
60-69	0	0	NA
70-79	0	0	NA
80-89	0	0	NA
90-99	0	0	NA
100-109	0	0	NA
110-119	0	0	NA
120-129	0	0	NA
130-139	4.06	24685	3
140-149	4.12	25050	5
150-159	4.29	26083	5
160-169	4.26	25901	5.5
170-179	4.17	25354	5.75
180-189	4.23	25718	6
190-199	4.51	27421	6
200-209	5.15	31312	6
210-219	5.96	36237	7
220-229	6.59	40067	7
230-239	7.12	43290	8
240-249	11.86	72109	10
250-259	16.06	97645	10
260-269	16.11	97949	10.5
270-279	15.99	97219	10
280-289	15.89	96611	10
290-299	16.66	101293	10.25
300-309	5.83	35446	6.5
310-319	0	0	NA
320-329	0	0	NA
330-339	0	0	NA
340-349	0	0	NA
350-359	0	0	NA

With the necessary data gathered it was time to begin calculating the wave climate. This was done with code presented in Weggel and Douglass (1985) and updated for use in popular spreadsheet form. As mentioned before the calculations follow the suggestions of the USACE Shore Protection Manual. The first step in the process was to correct wind speed for averaging time and height of anemometer, which was 2 minutes and 13.5 m or 44.3 ft above mean sea level. This step transformed the data into compatible input for the following calculations of wave climate.

Now for every ten degree section, the previously tabulated values of fetch and average depth across the fetch were melded with recently transformed wind data to arrive at a wave climate for each directional segment. This was done for each wind speed interval of record in each directional segment. Then the significant wave height of each directional speed was tabulated and this was coupled with wind data frequency analysis in order to produce a frequency analysis of the wave heights over the twenty year period of record. This shoreline only has moderate wave energy impacting the shoreline. All but 0.021 % of all the times of record were wave heights predicted to be less than 2.5 feet. This is relatively low energy environment, but one which is still too energetic to support a shoreline replanting effort without the presence of some wave stilling device. A rule of thumb for shoreline plantings is that the infrequent storms wave height should not be more than 1 ft or 0.34 m, and *Spartina alterniflora* will not readily colonize an area if the 80 percentile wave height is over 0.20 m (Roland and Douglass, 2005). A summary of the wave climate analysis is presented here.

Table 3.2 Hindcast Wave Climate Frequency Analysis

Wave Height (ft)		Occurrences	Percent Frequency	Running Total of Frequencies
0-	0.25	18837	24.2	24.2
0.26-	0.50	29364	37.7	61.9
0.51-	0.75	17729	22.8	84.7
0.76-	1.00	7034	9.0	93.7
1.01-	1.25	2987	3.8	97.6
1.26-	1.50	1127	1.4	99.0
1.51-	1.75	353	0.5	99.5
1.76-	2.00	290	0.4	99.8
2.01-	2.25	98	0.1	99.9
2.26-	2.50	22	0.0	100.0
2.51-	2.75	9	0.0	100.0
2.76-	3.00	4	0.0	100.0
3.01-	3.25	3	0.0	100.0
3.26-	3.50	1	0.0	100.0
	Total	77858		

Waves are also created in the Bay by vessel wakes. One major location of vessel wake production is the two shipping channels in the Bay. Barges use the Intercoastal Waterway on the South side of the Bay. Very large ocean-going vessels frequently use the ship channel to the Port of Mobile and can create very large wakes as they travel into and out of port. These ship waves will have little affect on the shoreline of interest because of the large distance the waves have to travel to reach the shoreline.

3.2 Longshore Transport

An understanding of the longshore transport processes is essential for most coastal engineering projects. The USACE Coastal Engineering Manual (CEM) says it is, “among the most important nearshore processes that control the beach morphology, and determines in large part whether shores erode, accrete, or remain stable.” Longshore transport is caused by waves breaking obliquely to the coast combined with local and regional nearshore current patterns. This means that sediment will move up or down a beach depending upon the direction of wave approach and current. This is the concept of along shore transport, or longshore transport.

Longshore transport is most commonly estimated by the use of an energy-based longshore transport formula, known as the “CERC equation.” The relationship between transport and deepwater wave energy was first developed in 1938 by a Danish engineer, Munch-Peterson, and because he did not have wave data he used wind data to estimate the longshore transport direction. This laid the foundation for the development of the CERC formula, which was carried on by the Scripps Institute of Oceanography in 1947. The formula continued to be updated until the publication of the Shore Protection Manuals in 1977 and 1984 (CEM, 2002). These many years of research produced this equation.

$$I_l = KP_l \tag{3-1}$$

This equation is commonly known as the CERC formula. I_l is the immersed weight transport rate, which is the volume transport weight of solids alone. K is an empirically-determined dimensionless proportionality constant. P_l is defined as the potential longshore sediment transport rate. This relationship can be coupled with what is known about shallow water wave theory and a conversion of I_l to a total volume transport rate to produce the following equation.

$$Q_t = K\left[\frac{\rho\sqrt{g}}{16\kappa^{\frac{1}{2}}(\rho_s - \rho)(1-n)}\right]H_b^{\frac{5}{3}}\sin(2\alpha_b) \tag{3-2}$$

In this equation, Q_l is the total volumetric longshore transport. K once again is an empirical coefficient, which is equal to 0.39 when working with significant wave heights, which is what will be done in this analysis. Ρ is the density of water, 1025 kg/m^3 for salt water and 1000 kg/m^3 for fresh water. G is gravity and equals 9.81 m/ sec^2. Κ is the breaker index for the beach. The breaker index is 0.78 for flat beaches and ranges to more than 1 depending upon beach steepness. P_s is equal to the density of the sediment, which is assumed to be sand and therefore have a density of 2650 kg/m^3. *N* represents the porosity of the sediment and is assumed to 0.4 for most conditions. H_b represents the significant wave height acting on the beach and will be obtained from previous calculations of the wave climate. The final variable in the equation is α_b and it represents the wave breaker angle with respect to the beach (CEM, 2002).

The CERC equation was used in this project in order to estimate the direction of longshore sediment transport along the study area. A spreadsheet was developed to compute the volumetric longshore transport which would be caused by all wave heights from all quadrants in the wave climate analysis. These values were tabulated and then compared with wind speed and direction records since 1987. A mesh of these data was then used to determine longshore transport contributions by each wave climate occurrence. All of these data was then gathered for each quadrant in the analysis and plotted as a longshore sediment transport rose in Figure 3.12. It is seen that there are two significant longshore transport directions for this shoreline. The dominant direction of transport is from north to south along the coast, although there is a south to north component also. These processes are not operating at the same time but at different times and probably different seasons, depending upon weather patterns.

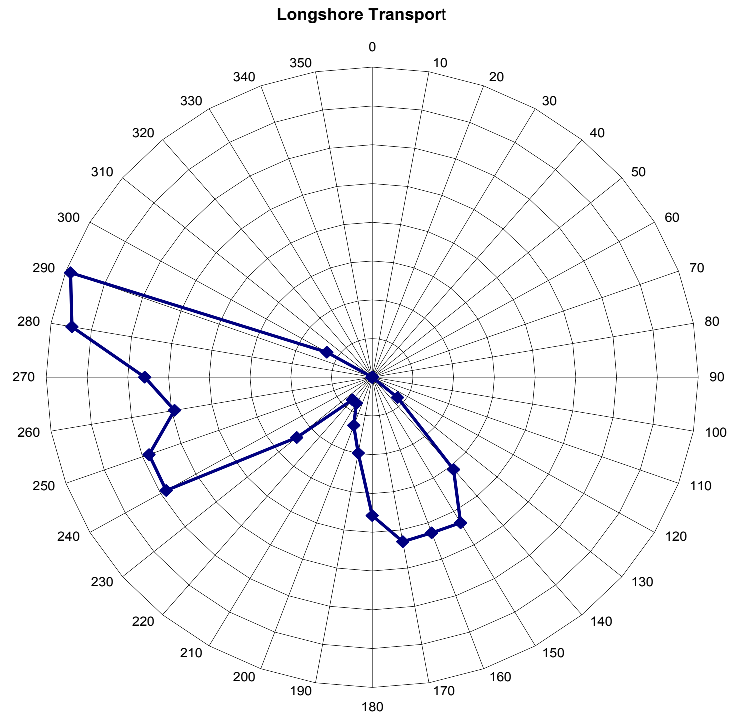

Figure 3.12 Longshore Transport Rose

3.3 Cross-Shore Transport

While longshore transport of sediment is driven by waves breaking obliquely to the shoreline, cross-shore transport is due to the on- and off-shore movement of sediment associated with wave action. The history of the study of cross-shore transport is quite short when compared to the study of longshore transport. Longshore transport study was begun around 5 decades ago, whereas the study of cross-shore transport of sediment is a little over a decade old (CEM, 2002). The idea of cross-shore transport is that under a wave crest a sediment particle is suspended to some proportion of the wave height, H_b, and then must return to the bottom with a fall velocity, ω. The time to fall to the bottom will be H_b/ω. If the time is less than half of the period, then onshore deposition of sediment will occur. If the time is more than half of the wave period, then offshore movement of sediment is occurring (CEM, 2002). This process of suspension, transport, and deposition is cross-shore transport of sediment.

Another important concept for understanding the coastal processes associated with this type of work is the depth of closure, h_c. Depth of closure is the depth of water out from the shoreline of interest in which the movement of sediment doesn’t affect significant changes in water depth. Wave tanks were used to test for this property and several empirical equations proposed. The equations relate the depth of closure to the effective height, which is defined as the height of waves which have a probability of occurrence of 0.137 percent of the time. In other words it is the wave height which is exceeded only 12 hours per year. The first expression as introduced by Hallermeier is

$$h_c = 2.28H_e - 68.5\left(\frac{H_e^2}{g*T_e^2}\right) \tag{3-3}$$

, where H_e is the effective wave height, T_e is the effective wave period, g is gravity (CEM, 2002). Also the equation is based on the assumption that the sediment has a relative density of 1.65. Birkemeier modified this equation based upon field measurements obtained at the U.S. Army Field Research Facility with the Coastal Research Amphibious Buggy (CEM, 2002).

$$h_c = 1.75H_e - 57.9\left(\frac{H_e^2}{g*T_e^2}\right) \tag{3-4}$$

Birkemeier also noted that a good approximation for the depth of closure is

$$h_c = 1.57H_e \tag{3-5}$$

All of these approximations were considered in order to build an intuitive understanding of the system for this project and to check against one another. They are presented here in Table 3.3.

Table 3.3 Depth of Closure

Depth of Closure
by Jared McKee

Input	English	or	Metric
H_e =	2 ft		0.6096 m
T_e =	3 sec		3 sec
g =	32.2 ft/sec^2		9.81 m/s^2

H_e = wave height which occurs 0.137 percent of the time
T_e = wave period which occurs 0.137 percent of the time

1st Approxiamation

h_c =	0.96 m	$h_c = 1.57\, H_e$
or		
h_c =	3.14 ft	
y_c =	15.6 m	
y_c =	51.3 ft	

2nd Approxiamation

h_c =	1.10 m	$h_c = 2.28 H_e - 68.5 \left(\frac{H_e^2}{g T_e^2} \right)$
or		
h_c =	3.61 ft	
y_c =	19.3 m	
y_c =	63.4 ft	

3rd Approxiamation

h_c =	0.82 m	$h_c = 1.75 H_e - 57.9 \left(\frac{H_e^2}{g * T_e^2} \right)$
or		
h_c =	2.70 ft	
y_c =	12.5 m	
y_c =	40.9 ft	

It is seen that the depth of closure has a range from 3.61ft (1.10m) to 2.70ft (0.82m). The deepest estimate of the depth of closure for the shoreline was given by the Hallermeier equation, while the shallowest depth was provided by the more elaborate Birkemeier equation (Dean and Dalrymple, 2004). These depths of closure estimations in turn led to an estimation of the distance to closure from the beach. This was accomplished by using the relationship

$$h_c = Ay^{\frac{2}{3}} \tag{3.6}$$

where A is a coefficient related to sediment diameter and y is the distance from shore (Dean and Dalrymple, 2004). In this analysis a grain size diameter of 0.45 mm was used and this, by way of Table III-3-3 of the CEM, led to a value of 0.153 for A. The distances to depth of closure for the study area range from 41 to 63 feet which seems reasonable.

The next thing to be determined was the fall velocity of the sediment. This will be used in conjunction with the wave height at breaking and the wave period. Two different estimations of fall velocity will be used. The first estimation of the fall velocity of the sediment is determined by the use of Stokes Law which relates the fall velocity of a sphere through a liquid to the particle density, particle size, and dynamic viscosity of the fluid through which it is falling. Stokes law was presented in 1851 and is presented here.

$$\omega = \frac{((\rho_s - \rho)gd^2)}{18\mu} \tag{3-7}$$

where ω is the fall velocity, d is the average diameter of the sediment particles which comprise the beach, and μ is the dynamic viscosity of water.

Most of the variables in the equation are known quantities, with the exception of diameter. The average diameter of sediment was obtained by performing a sieve analysis of sediment collected during trips to the project area. The standard geotechnical procedure for the grain-size analysis of coarse sediment was followed. Sieve numbers 8, 16, 30, 50, 100, and 200 were used with a dual stack mechanical shaker. It was determined that the median sediment diameter of the project area beach is about 0.45 millimeters (mm) with sediment sizes getting smaller further from the shore, as is to be expected. Individual grain size analysis and graphs produced from such are presented in Appendix E.

Now that a good estimation of the diameter of the sediment has been achieved, it is possible to quantify the fall velocity of a particle. This fall velocity will lead to an estimation of the cross-shore transport for the project area. The Stokes Law is well documented and commonly used for the approximation of fall velocity, and in the spirit of tiered-analysis the Rouse Chart from Dean and Dalrymple (2004) will also be used to further refine the estimation of the fall velocity of the sediment particles and therefore the estimation of cross-shore transport. A fall velocity of about seven (7) centimeters per second was given by Rouse chart for an average grain size of .45 mm and water at 20˚ Celsius. The calculation of Stokes Law led to a value of around eighteen (18) centimeters per second and is presented in Table 3.4. This difference in fall velocity by a multiple of two will make a considerable difference in cross-shore transport along the shoreline. This is where a certain amount of engineering judgment is required in order to characterize the system in as truthful a manner as possible. The tabulated value from the Rouse Chart will be used as the primary estimate as Stokes Law is based upon laminar flow around the particle.

Table 3.4 Fall Velocity by Stokes Law

Fall Velocity
by Jared McKee

Input			**Output**			
ρ_s =	2650	kg/m^3				
ρ =	1000	kg/m^3	**fall velocity**	**V =**	**0.182098**	**m/s**
g =	9.81	m/s^2				
μ =	1.00E-03	N*s/m^2				
r =	0.000225	m				
d =	0.00045	m				

A fall velocity model was applied to determine the direction of cross-shore transport. It was based upon a concept developed by Robert Dean in 1973 and presented in Dean and Dalrymple (2004). This concept was discussed in the first paragraph of this chapter, which explains the relationship between fall velocity, period, and wave height. Presented in equations the concept looks like this, which is the condition necessary for onshore transport.

$$\frac{\beta H_b}{\omega} < \frac{T}{2} \tag{3-8}$$

or rearranged

$$\frac{H_b}{T\omega} < \frac{1}{2\beta} \tag{3-9}$$

or rearranged for in most readily comprehensible form,

$$0 < \frac{1}{2\beta} - \frac{H_b}{T\omega}` \tag{3-10}$$

In the previous equations H_b is breaking height of waves, T is period of waves, ω is the fall velocity of the sediment, and β is a constant which was found by Dean to be around 0.3. This creates a static known quantity in the first term, while the term on the right is fully dependent upon inputs from the system. Therefore, according to this logic, a positive value for the previous equation will result in a net onshore transport for that wave height and period, while a negative value would represent offshore transport of material, and zero would connote no net movement of material on- or offshore.

By using this method on every wave climate in the previously developed hindcast, an idea of the cross-shore transport processes was formed. This analysis was dependent upon fall velocity of sediment, depending upon whether the Rouse Chart and Stokes Law estimation were used. Therefore when a value derived from the Stokes Law was used, a different picture of the cross-shore transport was calculated than when the fall velocity derived from the Rouse Chart was used. Interestingly, the value of fall velocity obtained from Stokes Law leads to onshore transport for all wave climates. But when using the fall velocity given by the Rouse Chart offshore transport is shown to occur at higher wave heights. This is a situation which seems to be more logical. Graphs of transport potential versus wind speed for each case are presented in Figures 3.13 and 3.14. The vertical axis of each of the figures is not quantified. This is because of the uncertain nature of sediment transport. These figures present a qualitative view of the cross-shore sediment transport, allowing for the determination of winds which dominant this process. Wind speed is used as the horizontal axis and it should be understood that the wind speed is directly linked to wave height and period, which drives these calculations.

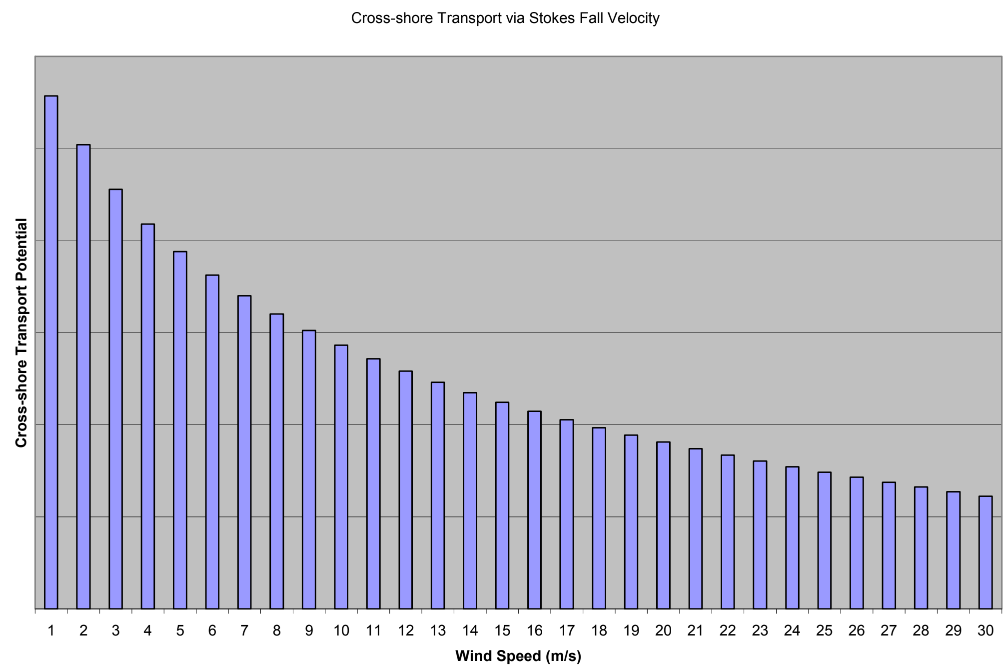

Figure 3.13 Cross-shore Transport Potential via Stokes Fall Velocity

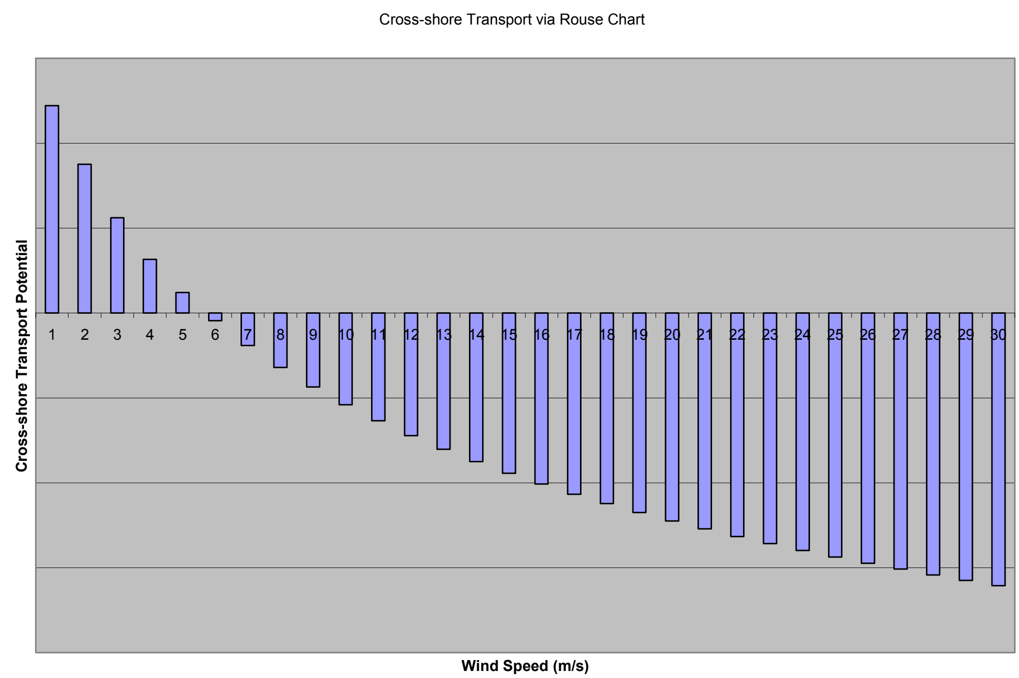

Figure 3.14 Cross-shore Transport Potential via Rouse Chart Fall Velocity

These graphs show that the difference in fall velocity makes a large difference for the picture of the cross-shore transport in the study area. In the case of the a high fall velocity as proposed by the Stokes Law yields a situation that is completely constructive, which would be a surprising case. A more probable picture is present by the graph of cross-shore transport potential as derived from the Rouse Chart fall velocity. This graph (Figure 3.14) shows cross-shore transport is constructive at lower wind speeds and is destructive at wind speeds of 6 m/s (~13 mph) and higher. But this graph is also misleading as it seems to show the majority of the cross-shore transport is in the offshore direction. A more complete interpretation of the cross-shore transport is presented when cross-shore transport potential is coupled with wind speed occurrence probability data, as is presented in Figures 3.15 and 3.16.

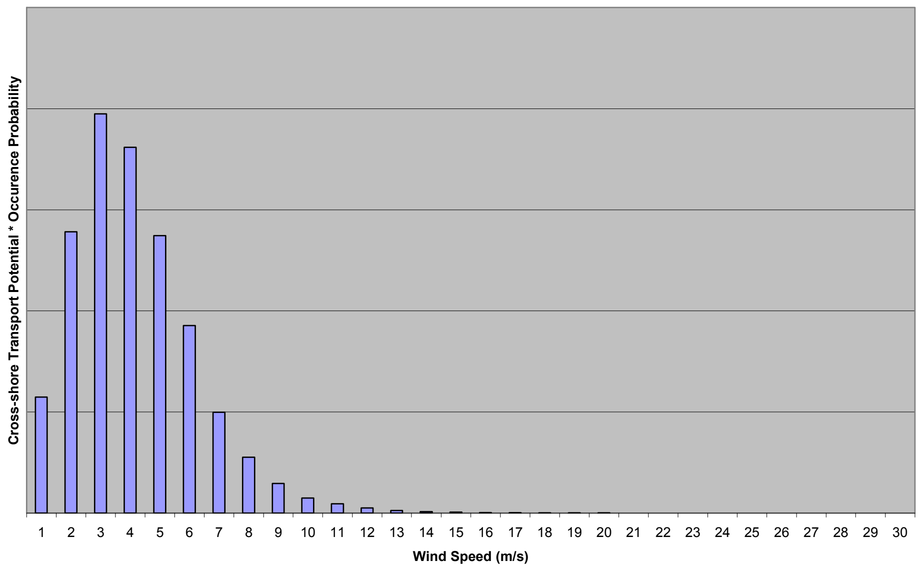

Figure 3.15 Cross-shore Transport Potential via Stokes Law Coupled with Occurrence Probability

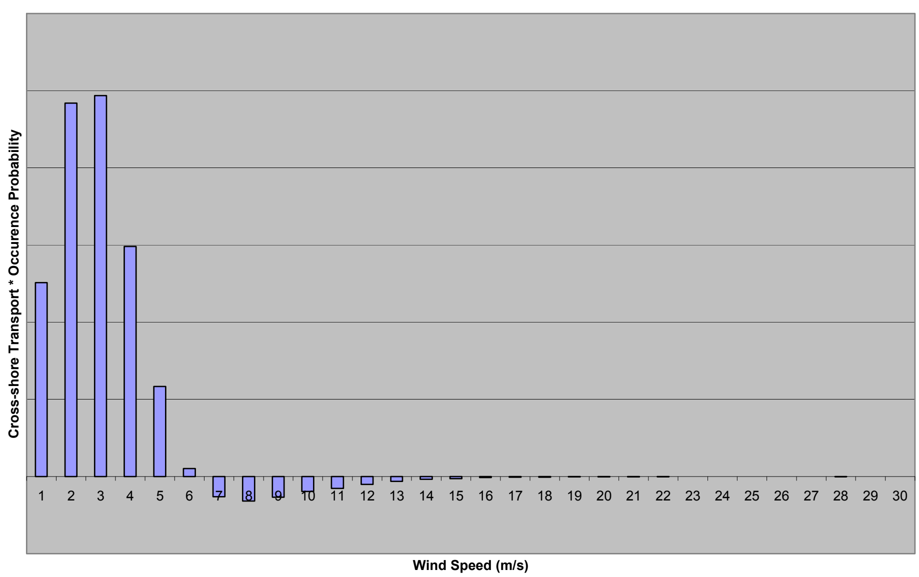

Figure 3.16 Cross-shore Transport Potential via Stokes Law Coupled with Occurrence Probability

The last chart, Figure 3.16, seems to present the most reasonable assessment of the cross-shore transport in the study area. It shows that there is a great deal of constructive potential at lower wind speeds and some destructive forces at the higher wind speeds. The beach is gradually being built up during most on the year, with low wind speeds and small waves moving sediment onshore. Then during large wave events the beach is being carried out to the bay at a much faster rate than it was being brought on to shore. This concept of accretion and erosion at different wave heights is a basic coastal processes concept and should be realized at all times during the analysis and design process.

3.4 Inherent Uncertainty of Transport Estimations

Sediment transport theory is not fully developed. There is not even a complete understanding of the sediment transport in rivers and streams, which are generally uni-directional with a relative constant density of water. So it is obvious that for a tidally-influenced and density variable waterbody like an estuary, it will be even more difficult to quantify the amount of sediment transport in the system. Therefore qualitative estimations are sometimes more helpful than trying to quantify the amount of transport. This still gives a relative picture of the sediment processes in the area without giving misleading numbers that could be misused. The inherent uncertainty of sediment transport can easily be illustrated in the estimation of fall velocity by Stokes Law as well as the Rouse Chart. Both of these methods assume that the particle falling thru the liquid is spherical in shape, when most of the beaches this is used for are sand covered. Most sands are not spherical, they are more likely random fractured patterns which have some sides and edges. Albeit, some sands, like aragonite which occurs in the Bahamas, are generally well-rounded and somewhat spherical (Dean and Dalrymple, 2004). But this study area is unfortunately not located in the Bahamas and the sand grains are fractured and angular. Also Stokes Law assumes laminar flow around the falling particle, which is surely not occurring in this study area. Therefore good engineering judgments are necessary to glean the pertinent information about littoral transport from these estimations.

3.6 Satellite Photographs

Satellite photography can be very helpful if it can be obtained. With satellite photographs, it is possible to get an idea of the regional sediment processes occurring in the area, as well as the circulation patterns in the waterbody.

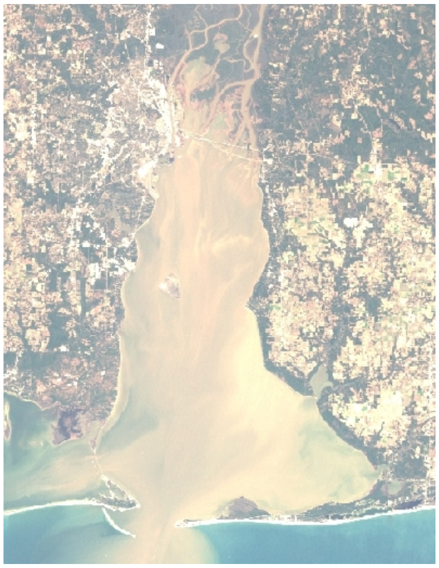

Figure 3.17 Mobile Bay LANDSAT Photo 06.Jan.03

Figure 3.17 shows Mobile Bay with a very great deal of suspended sediment and a considerable sediment plume exiting between Dauphin Island and Fort Morgan at the bottom of the picture. It is also noticeable that sediment is moving westerly into the Mississippi Sound also. The majority of sediment can be seen to be coming from the Mobile Delta in the top of the picture. This picture was after a large rain event which created much runoff and erosion, and this will led to suspended sediment and deposition in the Bay and bypassing out to the Gulf of Mexico. In this picture the sediment plume does not seem to be as concentrated by the study area as most of the rest of the Bay. This suggests that the dominant hydrologic processes occurring at that moment are moving sediment mostly longitudinally. Tidal influences coupled with Mobile River pushing flow south are probably the dominant forces in suspended sediment leaving the bay. This picture shows an outgoing tide, while an incoming or rising tide would tend to "push" the sediment plume over to the sides of the bay, around the study area.   The photographs in Figure 3.18 show the Bay during different emptying phases.

(a) (b)

Figure 3.18 Mobile Bay LANDSAT Photos (a) 18.Dec.04 (b) 23.Dec.94

The pictures in Figure 3.18 demonstrate how the Bay can transport sediment in very different ways. Figure 3.18b shows how sediment can be pushed into Bon Secour Bay and Southeast Mobile Bay by an incoming tide. The picture also suggests that there is relatively little circulation or current in Bon Secour Bay. Figure 3.18a shows a situation where there is a lot of sediment entering the system but it is being transported south fairly quickly. According to wind records of this time the majority of winds were from the North. Northerly winds in the winter have the tendency to "drain" the Bay and push the water level down. This would contribute to a situation like a low tide where sediment is transported relatively quickly through the system.

(a) (b)

Figure 3.19 Mobile Bay LANDSAT Photos (a) July 8.Jul.00 (b) 27.May.05

The photos in Figure 3.19 show the Bay with suspended sediment around the shorelines of the Bay. This is caused by high winds over the bay that cause vertical turbulent mixing of the shallower waters of the Bay. In the on the left, there was a dominant wind from the North, Northwest, West on the previous day and the day of the photograph. The photograph on the right was taken after several days of high winds from the West. The resuspension of sediment by wind turbulent mixing is a major process in the Bay. But the majority of sediment processes in the region are dominated by the inflows from the Mobile-Tensas River Delta.

3.7 Analysis Conclusions

The shoreline in the area has been experiencing moderate wave energy with 99.9% of the wave heights less than 2.5 feet. But even this moderate wave energy is enough to erode the shoreline and not allow full establishment of intertidal grasses. The only fortification for the shoreline is a row of submerged cypress stumps from a time when the shoreline was farther seaward. Longshore transport for the shoreline is dominantly from the North to the South, although there is a considerable transport in the other direction. The direction of transport is dependant upon the time year. Ship waves from the channel will also increase longshore transport at the study area. Cross-shore transport of the area is generally constructive but during periods of high wave heights there is a very high erosional potential. These extreme wave events are the probable cause for rapid and episodic shoreline retreat into the wetland and should be addressed in an erosion mitigation plan. After studying satellite photographs of Mobile Bay and talking with Dr. Kyeong Park of DISL, it was determined that currents in the area are not significant forces acting on the shoreline. There is little current and circulation in that section of Mobile Bay and Bon Secour Bay. Scarp erosion is a dominant erosional process along the beach. This undercuts the natural defense systems of the shoreline and puts the shoreline at risk of a major erosional event. All of this leads to wave energy impacting the beach/berm/wetland system as being the most important threat to the health and survival of this system. In order to mitigate erosion and protect the health of the system, the wave energy should be damped before it reaches the shoreline and the area must be fortified to be able to withstand the waves which impact the shore.

CHAPTER 4

DESIGN CONCEPTS

The shoreline in coastal Alabama is constantly changing because of a variety of natural processes and human activities (Stout, 1998). It is for this reason that property owners and managers are counseled to build as far landward as possible to allow these processes to occur naturally with minimal property damage. Even then it may be necessary to implement shoreline stabilization measures in order to retain as much land as possible, but to introduce a hard static land and sea barrier would disrupt the natural cycles of shoreline change and may lead to unforseen problems. The choice of the shoreline stabilization technique can have beneficial or detrimental effects on the shore, beach, and estuarine health (NCCF, 2000). It is the intention of this chapter to provide concepts and ideas for a healthy and helpful shoreline erosion mitigation plan for the Swift Tract Site in Southeast Mobile Bay.

The common shoreline erosion control technique found in Mobile Bay is bulkheading, or the building a vertical wooden or metal structure at the shoreline, which, if successful, stops landward migration of the beach but does not address the sediment deficit which is the cause for erosion in the area (Douglass, 1999). This leads to an increase in vertical erosion in front of the wall. This can effectively destroy the intertidal area of the shoreline which is imperative for healthy estuarine ecosystem function (Douglass, 1999). The North Carolina Coastal Federation (NCCF) also notes that “bulkheads may be treated with wood preservatives which have been found to be toxic in the marine environment” (NCCF, 2000). Once the hard surface of the bulkhead is submerged it provides an environment for some organisms which would not normally grow in an intertidal shoreline. Nonetheless, it is generally considered that bulkheads do little to advance the ecological integrity of an area and probably adversely affects the water quality and natural processes in a waterbody.

Therefore it necessary to continue to develop reliable and robust shoreline erosion control solutions that do not negatively impact the surrounding ecosystem and even promote healthy ecosystem evolution. One way to do this is to look to the natural systems of the area in order to attempt to replicate that system and give it the best chance for a thriving survival. One of the oldest land management techniques is the use of plants to stabilize soil and reduce erosion and is what has been called “following the natural model” (Melby and Cathcart, 2002). One aspect of the natural model found around and in the study area is the fringe wetlands and marshes. These types of estuarine shorelines are dynamic places that are a crucial part of the ecosystem and should be treated as such. It is important to preserve and promote this natural shoreline protection system.

There are many ways to effectively protect a shoreline while improving the surrounding ecosystem. One way this can be accomplished is by restorative plantings of intertidal species along shorelines with sparse or no vegetation. But it can be very difficult to establish new plantings for a fringe wetland in areas with high wave energy and for those situations some method is needed to lessen the wave energy impacting the shoreline. One way this can be achieved by placing breakwaters away from shore and below mean high tide. When waves pass over the breakwater the waves ‘break’ and crash, dissipating much of their energy through turbulence before reaching the shoreline and thus greatly decreasing the erosion potential of the shoreline and increasing survival potential of the fringe wetland. In the past, these breakwaters have been made of piles of riprap, and from formed concrete structures in higher energy areas, while in lower energy areas a vertical wooden breakwater has been used with success (Broome, et. al, 1992). All of these technologies relied on material being brought from somewhere else, except for possibly the wood, which could have been grown close by, but this still would have to be processed. It would be preferable if the structures could be made from locally available, previously used, non-toxic material. When properly applied, this concept could decrease project cost while reducing and improving the environmental impact of the project in the surrounding area.

A combination of these concepts and measures could be used to mitigate the shoreline erosion at the project site. An offshore oyster reef breakwater could be employed to lessen the wave energy impacting the shoreline. Submerged aquatic vegetation and lower intertidal grasses species would be planted around existing cypress stumps, which are presently fortifying the shoreline. The existing shoreline and berm could also be planted with native grasses and shrubs found in the area. In the intertidal zone and swash zone grasses, predominately being *Spartina patens,* and *Spartina alterniflora*, would be planted. This can transition to Saw Grass, *Cladium jamaicense*, and common shrubs found in the area, mostly Wax Mrytle, *Myrica cerifera*. Also the shoreline would continue to be fortified by planting native Pondcypress, *Taxodium ascendens,* in the berm and higher layers of the freshwater wetland. This design concept is an attempt to improve the ecosystem as a whole by addressing all the zones and transitions between zones from out in the bay to the shoreline and landward into the berm and freshwater wetland. This approach of improving coastal protection from the sea to the forest is necessary and responsible because shoreline migration is a natural process and the best thing that can be done is to prepare the area to be able to transition between zones as sea level rises or falls locally and shorelines subside or accrete. These design concepts are not the sort to create a new static solution to fix the shoreline at its current position but are assistance for the current ecosystem to be able respond and adapt to the ever changing environmental pressures such as sea level rise, land subsidence, dune growth through saltation, and major storm events. These design concepts would help protect the shoreline from erosion and increase the ecological integrity of the area.

One of the key concepts of this design is to recognize the connections between zones of the shoreline. So much of science is reductionist, breaking things down into smaller and smaller parts in order to understand something about the nature of the subject. This preconceived perspective has contributed to design which focuses very intently upon one part or section of the shoreline system instead of looking at the entire continuum from offshore to landward and both up-coast and down-coast. This thesis will recognize shoreline protection alternatives which will promote a healthy ecosystem despite changes in conditions. It is without question that this shoreline will migrate, so therefore rather than attempting to maintain an arbitrary location this holistic design concept will facilitate the natural evolutionary processes of the shoreline. The shoreline may migrate landward, but not in a devastating massive erosion event. These erosion control measures could also cause the shoreline to accrete and move seaward. By emphasizing shoreline plant community succession and movement with sea level rise or shoreline elevation change, this area of shoreline would be more resilient and robust and would have higher ecological integrity for a variety of changing situations.

A fringe wetland/SAV revegetation/offshore breakwater design is also preferable because it can be less costly than other less ecologically friendly alternatives. This design would also be more attractive and aesthetically pleasing than many of the current shoreline protection schemes.

4.1 Oyster Shell Reef Breakwater

One of the most frequently used materials for breakwaters in medium energy areas is a riprap or rubble mound piled atop of underlying structure, usually a geotextile, to prevent settling into the sediment. This creates a structure which would be quite resilient to even large waves in the project area if the stones are large enough. It also presents a chance for the creation of a hard substrate which, in an area like Mobile Bay, will be a natural place for the recruitment of oysters to create a reef. Oyster reefs are the temperate analog to coral reefs found in tropical parts of the world. On the basic singular level, oysters can improve water quality of an area as they are filter feeders which filter great amounts of water. This is greatly reduces the amount of suspended sediment, phytoplankton, and other particulate matter in waters surrounding a developed oyster bed parallel to the shoreline (Stout, 1998). These are secondary ecological benefits that were accrued by creating an advantageous area for oysters to settle while damping wave energy as it enters the fringe wetland. This is the most important benefit from the oyster reef because the fringe wetland and native plantings would have little chance of survival in an area with such a large fetch and wave energy. And without the presence of the fringe wetland the offshore low-sill breakwater would have little chance of protecting the shoreline during a major episodic event in which the waves would pass over the reef then relying on the plantings, their root mat, and berm plants and trees to damp the wave energy and resist the storm-induced erosion.

The addition of an oyster reef as an offshore breakwater would also greatly improve the habitat for aquatic species. The crevices and voids of a three dimensional oyster reef provide fish habitat for a variety of species and are attractive to estuarine life, from benthic organisms to small and large fish to wading birds and raptors, thereby enhancing the ecological function around the study area (Stout, 1998). A healthy fishery area would surely attract human fisherman as well which would invariably/hopefully notice the shoreline protect design and appreciate it for improving the overall quality of the area. This can be a way to passively educate the public and thereby change public opinion about what a reliable shoreline protection design can be.

4.2 Native Grass Plantings

The creation or restoration of fringe wetlands would benefit the system in many ways. The environmental services provided by wetlands are quite considerable. They contribute to the improvement of water quality by: removing nutrients, processing chemical and organic waste, catching sediment runoff, converting solar energy into biomass, and buffering land areas from wave damage (Melby, 2001). Wave energy would be damped and soil stabilized by marsh grasses, thereby reducing erosional effects. The thousands of stems and leaves of the *Spartina* grasses would cause much turbulence and very high surface roughness for the water to pass over. This would create much resistance, slowing the water down, and decreasing much of the energy which the wave was translating from wind to the shoreline sediments and causing erosion (Broome, et. al, 1992).

A wetland in the area could also act as a natural filter of upland runoff, reducing the amount of pollutants, sediments and nutrients entering the bay or waterbody. On a bulkheaded shoreline, sheet flow from the surrounding area during a large rain event flows down slopes and runs over top of the bulkhead and directly into the waters of the local waterbody. When this occurs in developed areas, all manner of pollutants can be introduced to the watershed, from things as harmful as mercury and other toxic substances to things as relatively benign as sediment and excess nutrients. Either way this unfiltered and unchecked sheet flow can be detrimental to the water quality of the receiving waterbodies. When sheet flow encounters a fringe wetland before entering the waterbody the flow must slow down for the same reason as waves slow down when they pass over the grassy areas. The reduction in velocity greatly reduces the transport capacity of the water keeping all manner of the unwanted material and nutrients from entering the waterbody. Some of these excess nutrients, which can cause detested and toxic algal blooms, can be acquisitioned by the wetland plants causing them to grow more healthfully and thereby better protect the shoreline.

The creation of fringe wetlands as an erosion control solution also contributes positively by improving fisheries and near shore habitat in the area. The periodically flooded grasses would give small fishes and the young of larger species protection and a place to feed and grow. This would create a preferable rearing ground for the young and increase the amount and health of the nekton population. These grassy shorelines would also provide habitat for the other marsh creatures such as the periwinkle snail (Author's Observation) as well as "present natural, attractive views from both the land and water" (NCCF, 2000).

Spartina patens is the dominant species found in the intertidal area of the project site. It is a low to medium height grass with a slender hollow stem and narrow linear leaves and resembles *Spartina Alterniflora* which can also be found, though not in abundance, in the project area. *S. patens* or Salt Meadow Cordgrass is typically found in “irregularly flooded salt, brackish, and tidal fresh marshes (often forming cowlicked mats, and reported to occur at times in regularly flooded zone); on wet beaches, sand dunes and borders of salt marshes” (Tiner and Rorer, 1993). Besides the upper plants acting as energy dissipaters, the fringe wetland would also begin to build a root mat of plant material and sediment that can become quite thick and much less apt to erode than a loose sediment shoreline and “causes the largest storm waves to break before reaching higher land areas” (Rogers, 1992). Once this root mat is established, it would persist and protect the shoreline even if the marsh grasses fail and die back because of a catastrophic event. It has been generally noted that if some marsh grasses are already growing around the area then there is a good chance that replanting would succeed. But shoreline plantings can be difficult to establish because of the different stessors such as, hypersalinity, sediment deposition, tidal inundation, wind, and scouring (O’Brien and Zedler, 2006). Some things can be done to assist the new plantings. Plants which are planted closer together or in clump patterns would survive better than plants widely and evenly spaced (Broome, et. al 1992, O’Brien and Zedler, 2006). Also, the availability of nutrient rich organic matter has also been found to be very helpful to the establishment of fringe wetland plantings (O’Brien and Zedler, 2006). By doing this the plants have a head start in their life and can therefore more rapidly revegetate the intertidal area and above and below the beach/berm/wetland system.

The Salt Meadow Cordgrass and Smooth Cordgrass plots could be planted with an average18-inch spacing and between three and five inches deep. Planting should occur during the late spring in order to give the plants the longest possible growing season in their new environment before the coming of winter winds and storms. Plants may be planted later into the summer but the chances for survival over the winter is much less as the plants do not have time to produce good root growth for stabilization and acquisition of nutrients. *Alterniflora* should be planted from mean tide level to mean high tide. *Patens* generally grows above *alterniflora*, between mean high tide and the high water line in storms, and would be planted in this zone with an overlap area around mean high water (Broome, et. al, 1992).

Scarp erosion is a problem along the shoreline that should be addressed by marsh toe support. This can be provided by aquatic vegetation planted seaward, around existing cypress stumps. Several species of submerged grasses could be planted in the study area. These grasses would provide toe protection for the intertidal grasses.. Species which are or have been commonly found around Mobile Bay should be used for this purpose. The most commonly found grass in high salinity areas of the Bay is Turtle grass, *Thalassis testudium,* which grows from rhizomes that may grow as deep as 10 inches. The grass blades are flat and ribbon like and can grow to lengths of 14 inches. The name Turtle grass refers to the green sea turtle, *Chelonia mydas,* which feeds on the grass (Turner, et. al, 2005). Another grass which could be used is Shoal grass, *Halodule wrightii,* which readily colonizes disturbed areas that are too harsh for Turtle grass (Turner, et. al, 2005). These grasses would provide a sediment stabilizing effect when the leaves reduce water velocities near the sediment surface allowing sedimentation and inhibiting resuspension of sediment and organic matter. The roots and rhizomes of the plants also provide structural support which binds sediments and slow erosion (Stout, 1998).

These sea grasses are also essential parts of the web of interactions in this ecosystem. SAV sequesters nutrients from the sediment and release the nutrients through their leaves into the water column (Stout, 1998). They provide food and habitat for fish, invertebrates, shellfish, waterfowl, and reptiles (Turner, et. al, 2005). They improve water quality in the area by producing oxygen in the water column. They also help by filtering and trapping suspended sediments which can bury oysters and the hard substrate which is necessary for spat growth. The grasses continue to help by sequestering excess nutrients, which sometimes help produce harmful algal blooms. The grasses would readily absorb these nutrients because they are essential for the growth and survival of grass beds (Turner, et. al, 2005). Along with these ecological advantages, the plants would fortify the sediment seaward of the intertidal grass species and would also help to further reduce water energy impacting the shoreline as their structure would create more surface roughness and thereby turbulence.

Very little research or management of submerged aquatic vegetation has occurred in Mobile Bay (Stout, 1998). Nonetheless, Judy Stout and Ken Heck of the Dauphin Island Sea Lab studied the survivability of transplanted Tape Grass, *Vallisneria americana,* in the Bay. They found a survivability rate of 87-100% in water less than 0.5 m deep (Stout, 1998). Although Tape grass would not be used in this project, as it is a freshwater species, it is still encouraging to know that re-establishment of SAV beds can be successful in and around Mobile Bay.

4.3 Berm and Freshwater Wetland

The berm could be planted with native trees, shrubs, and grasses already found in the area in order to fortify the berm against large storm events. The berm receives significant wave energy during high water level storm events which would cause the berm to retreat into the freshwater wetland behind the berm and thereby lose a part of an ecologically valuable natural asset. The added density of native plants would help to maintain the structural integrity of the berm and many help to accrete some sediment to the berm. This would help the berm to withstand a large wash out caused by a major episodic event. The berm could be planted with Wax Myrtles and Saw Grass would be planted on any spots in need of revegetation on the back side of the berm. Pondcypress would be planted intermittently throughout the wetland and berm in order to attempt to recreate the effect which must have been present sometime ago by evidence of the many stumps along the shoreline and some distance offshore. The trees would be planted intermittently in higher areas throughout the open wetland area, and be planted more densely closer to the shoreline and berm. This would fortify the berm and parts of the wetland, while creating a microclimate which is underdeveloped in the area.

In examining the other areas around the shoreline, the most notable difference between this shoreline which is eroding and the other shorelines in the area is the presence of trees along the shoreline. But not all of the trees seen on adjacent shorelines would be suitable for an intermittent wetland environment as is found behind the beach/berm shoreline system.. The presence of the wetland behind the berm is one of the things that makes this shoreline unique and important. It also limits the types of trees which would survive and thrive in the area. In an area such as this Pondcypress would be a good choice for planting. They are relatively fast growing tree which can tolerate inundation and some degree of salt water (Gilman and Watson, 1994). Other exotic trees are currently present in the study area and are surviving well. Most notably and profusely is the Chinese Tallow Tree, Popcorn Tree, or *Sapium sebiferum*. This tree is considered to be invasive by many, because it can rapidly colonize a variety of habitats, including the habitat found in the study area. It would be an ecologically ethical question as to whether or not to encourage the growth of this tree, which can out-compete many native species but grows readily and rapidly. Nonetheless, it seems that an important aspect of a holistic design for this shoreline would be the replanting of trees in the project area. Trees along the shoreline and in the wetland would provide much protection for the soil and plant communities around the trees as well as lessening the effects of storm surges and high winds on areas landward. Native Pondcypress trees could provide an anchor landward for the other aspects of the holistic erosion mitigation plan, while the oyster reef breakwater provides the seaward anchor.

4.4 Design Concept Conclusions

By employing a mesh of these erosion control technologies, the needs of the shoreline ecosystem will be met. These design concepts have used the natural world as their primary example and are based upon processes already occurring along healthy shorelines in the area and around the world. By using these all of these ideas, the shoreline is protected along its entire XYZ spectrum. The shoreline is protected down its entire length. The shoreline is protected from out in the bay with the breakwater in the surf zone, to the sea grasses and emergent grasses along the shoreline, to the larger upland grasses, shrubs, and trees of the berm and wetland landward area. The shoreline would also be fortified by these plant roots securing sediment below and forming protective root mats. The plants would also act to lift winds coming off the bay and lessen storm surge by creating more turbulent area for the water to move through. These technologies will also be much more beneficial for the native flora and fauna of the shoreline and bay than the dominant form of shoreline armament found around Mobile Bay. These design components can be used to address the problems of shoreline erosion and estuarine ecosystem endangerment.

CHAPTER 5

RECOMMENDED DESIGN

5.1 Scope of Design

This section sets forth a design for the control of erosion and shoreline restoration along the 1km beach/berm/wetland system in Southeast Mobile Bay. While this study accounts for the major erosional forcings along the shoreline, it should be understood that it impossible to fully characterize a system with all associated minor forcings. For instance, vessel wake effects are not considered in this design.

5.2 Design Components

In order to adequately address the forcings of sediment transport in the study area and prepare the beach/berm/wetland system for healthy shoreline migration, a holistic design that is compatible with surrounding environment is preferable. My design goals are listed here:

- Control shoreline erosion
- Improve local ecosystem integrity
- Minimal or no impact on downdrift shorelines
- Protect landward structure

- Use locally available, low-impact materials
- Maintain or enhance aesthetic appeal

In order for this type of design to come to fruition, several shaping principles and ideas must be recognized. The first idea is that the shoreline protection design should mitigate erosion while recognizing that shoreline migration is a natural process. It will not be attempted to hold a shoreline in one arbitrary place. To do so would be an inherent weakness that can lead to major failures of the protection system and a large pulse of sediment into the waterbody, negatively affecting many aspects of local biosphere. My design goal is to control erosion by enabling the shoreline to effectively change, evolve, and migrate in a natural and healthy manner. The design should position the shoreline to be able to transition easily with long term changes in water levels. Another design goal is that the design should positively affect the health of the local ecosystem. Doing harm to the existing biota in the area should be avoided. Therefore it is important to inspect healthy shorelines around the area to determine why they are succeeding and what is living there and in what relationships. By doing this, a design concept for the study area could be found which is not a stressor on the local ecosystem and uses native plants and local goods to improve the study area's erosion resistance and ecological function. Also, in order for the design to be the best that is capable of being and have a better chance of implementation, many different benefits should be produced for the project area. The design should mitigate erosion, be helpful to the local ecosystem, be beneficial for the public, protect the landward area behind the beach/berm and be aesthetically pleasing. A design which follows these concepts and ideas should address many of the issues facing this shoreline in way which is compatible with surrounding shorelines.

A design formulated to meet these goals, consisting of vegetative plantings and an offshore submerged reef, is presented in Figures 5.1 thru 5.5 and described below.

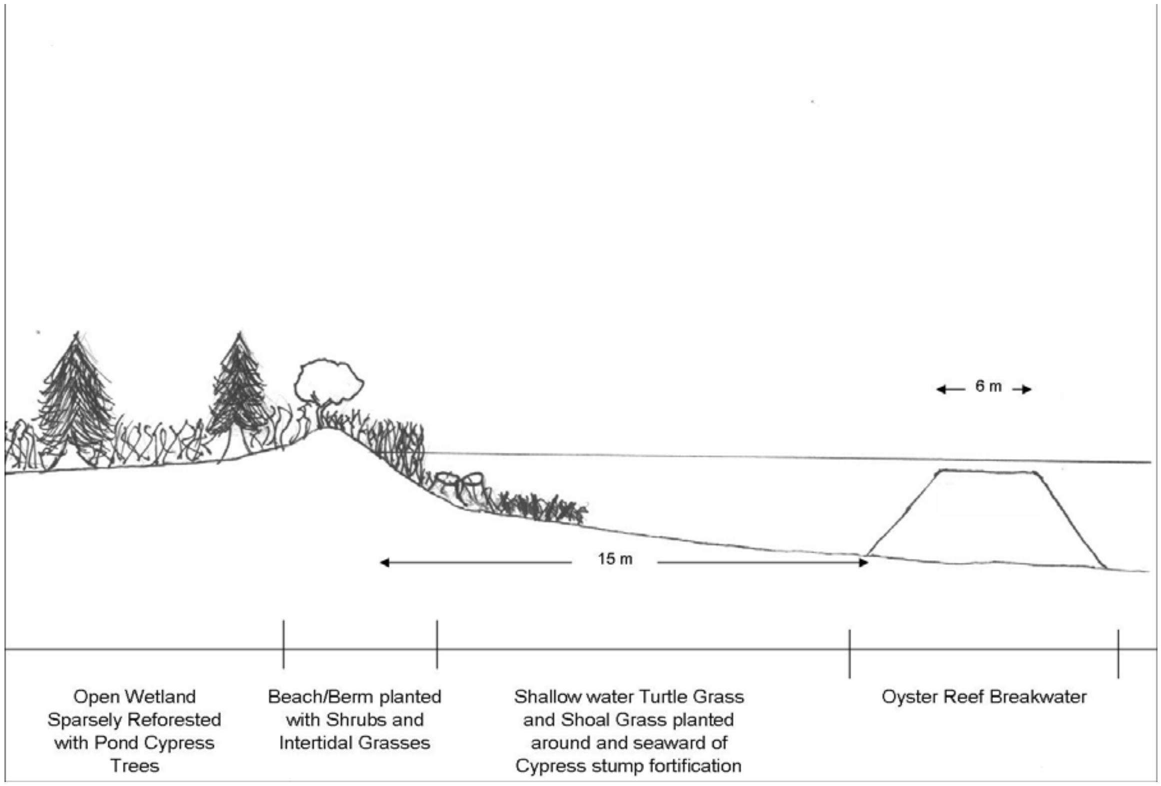

Figure 5.1 Section View of Design Plan

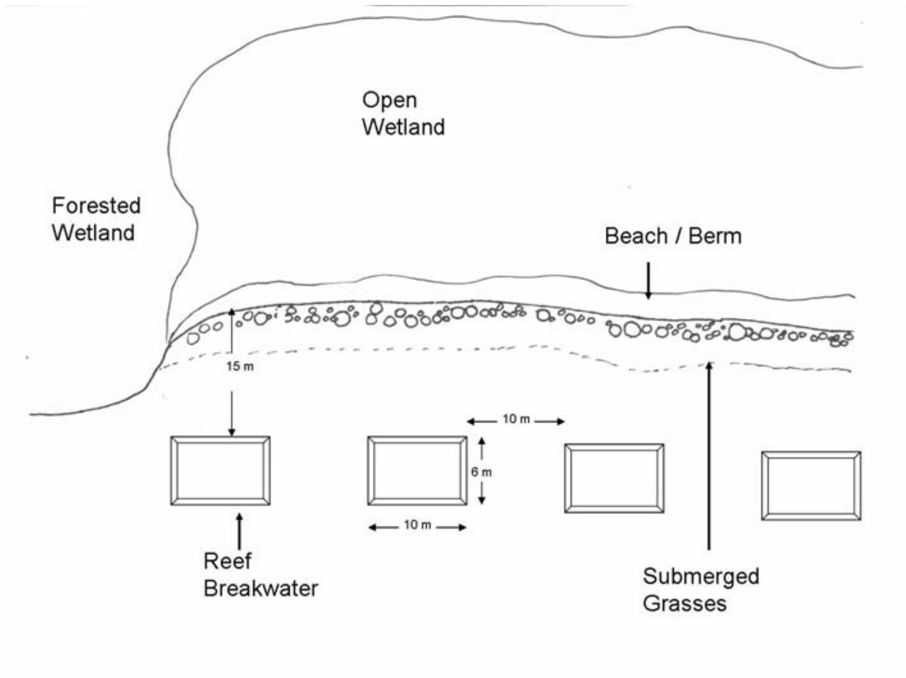

Figure 5.2 Drawing of North Side of Study Area

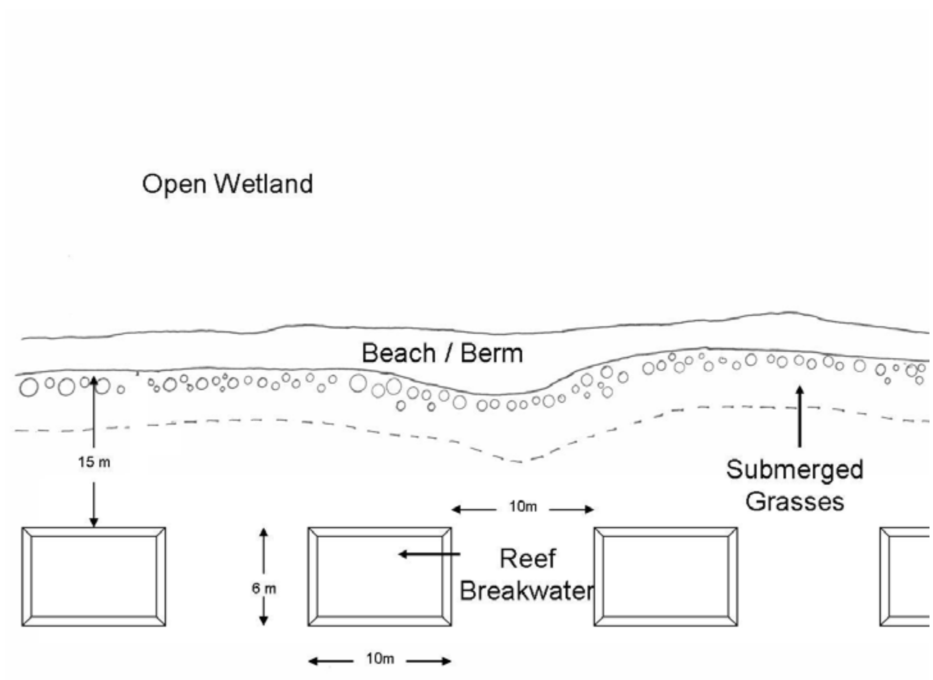

Figure 5.3 Drawing of Middle of Study Area

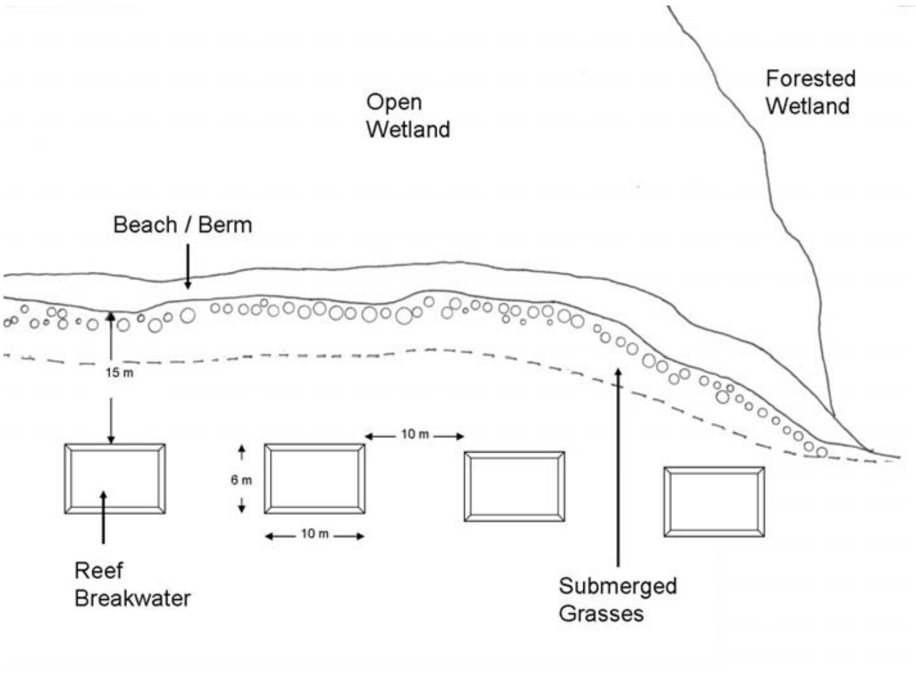

Figure 5.4 Drawing of South Side of Study Area

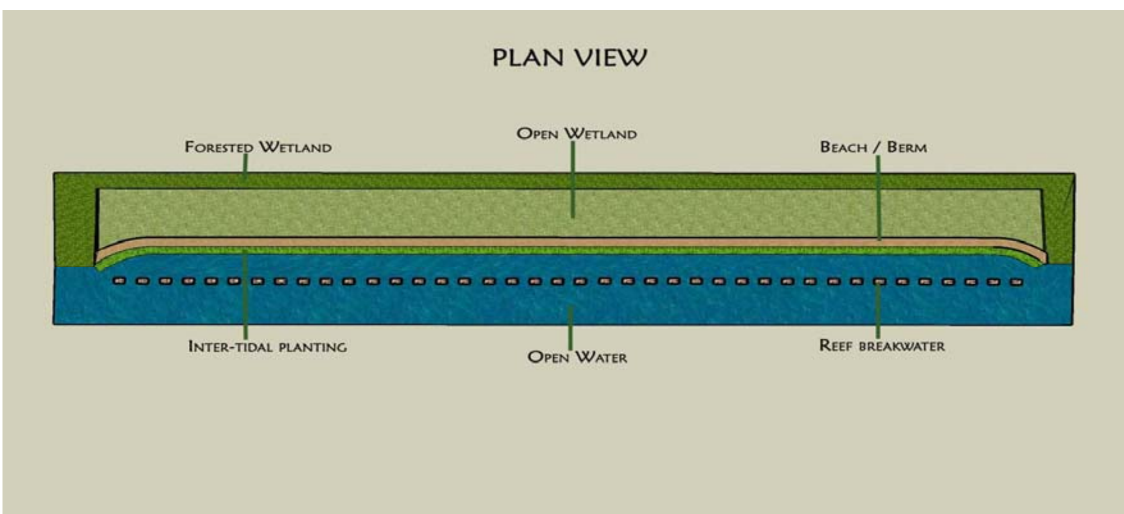

Figure 5.5 Entire Study Area Model

5.3 Vegetative Plantings

In following with these concepts, one noticeable difference between the shoreline of interest and the surrounding shorelines is that the other shorelines have a much greater density of trees along the shoreline and landward. This prevalence of trees along the other shoreline seems to protect and anchor the shoreline during large events. Even after some of the trees have died, the root structure helps hold the sediment in place and give a base for other plant life to colonize. Also, the aerial structure of the tree, the truck and limbs, will benefit the shoreline and landward area by reducing a high storm surge as well as lessening wind speeds and airborne transport of material. The wind-energy damping effect would be more prevalent for living trees with foliage, but large dead trees also play an important ecological role. Along bay shorelines, these large dead trees are often used by large birds of prey as nesting areas and lookouts while hunting. The presence of trees can benefit the health of the ecosystem on many different levels. Therefore, it would be a great benefit to the system to replant Pondcypress in the area, in order to repopulate the wetland and shoreline as it had been in the past and eventually provide habitat for large and small birds. Pondcypress trees are fast growing which can grow to height of 50-60 feet and have a spread of 15 feet (Gilman and Watson, 1994). This would lead to a plant spacing of 7.5 feet for a wall of Pondcypress, but this is not what is necessary as there will other plants to help fortify the shoreline. Plant spacings of greater than 10 feet will enhance wildlife habitat (Vince and Duryea, 2004). Along the back of the berm pond cypress trees should be planted with around 12 foot spacing, while the wetland plantings would have a much larger spacing of around 20 feet.

The planting of trees along the shoreline and back in the freshwater wetland will be just one part of a holistic shoreline design. The beach will also be fortified with additional plant materials. Common shrubs and small trees, such as Wax Myrtles, will also act to fortify the shoreline and survive the harsh conditions. It will also promote and preserve genetic diversity. One thing that will be avoided is planting a large monoculture of one species, which would make the design much less robust in erosion control and less ecologically valuable for the area. The Pondcypress will be planted sparsely in the open wetland area and more densely along the berm and landward side of the berm. Then the shrubs will be mixed in and interplanted along the berm and the landward slope of the berm. Also other desirable plant species, such as the Rose Mallow, will be planted for their aesthetic appeal. This interplanting of flora which grow at different heights will create a vegetative ramp which will protect landward area by “lifting” winds up and over as they approach across the waters of the bay.

The shoreline will continue to be fortified with grasses also found around the area. Saw grass will be planted in the higher sections above the tidal level and back in the wetland, although the wetland seems to be growing profusely and looks quite healthy. Saw grasses can be transitioned into Black Needlerush, already well established, on the berm and closer toward the tidal area. In the areas just below, Salt Meadow Cordgrass will be planted in the upper tidal range. This species should do especially well in the area as it can be found on a good deal of the shoreline already. Although it is robustly present, it is also troubled on the shoreline because this is the species which seems to be most commonly affected by the scarp erosion occurring in the area. In order to control this scarp erosion, transitioning from Salt Meadow Cordgrass to Smooth Cordgrass will happen next. The Smooth Cordgrass prefers to live lower in the tidal range than the Salt Meadow Cordgrass and should help to protect against undercutting of the root mat of the Salt Meadow Cordgrass. The different species of Cordgrass will form a cohesive mat that will be much more resilient than exposed sediment or a mat from a singular species. Below the Smooth Cordgrass in the lower tidal range and further out in the bay, submerged aquatic vegetation such as Turtle Grass and Shoal Grass will be planted. Both of these species are commonly found in the bay and Shoal grass reportedly readily colonizes disturbed sites (Turner, et. al, 2005). This makes it a good choice in sea grass bed establishment. Many of these grasses are already found in significant numbers, especially the species which grow higher in or out of the surf zone. Therefore not as many plants will be needed to revegetate the shoreline. A plant spacing of 18 inches is sufficient for successful establishment of the Smooth Cordgrass (Broome, et. al, 1992).

This spacing would be lessened to around 12 inches in this project in order to give the grasses more structural support and a better chance of establishment. This will more quickly protect the shoreline and will also be economically feasible as the shoreline planting will not be along the entire beach but only in areas devoid of vegetation.

This interplanting and transitioning of local flora will provide many benefits for the shoreline and the biotic community in the area. The sea grasses and intertidal grasses will protect and hold the sediment upon which it is established. The grasses will also decrease wave energy reaching the shoreline by increasing the surface roughness of the foreshore area and creating turbulence. The grasses are also places for young and small fish to feed and be protected from larger predators and harsh conditions of the open bay waters. Other invertebrate life will also benefit from the habitat enhancement in the area. But these shoreline and submerged plantings could not possibly be established without a breakwater to lessen wave energy reaching the shoreline.

5.4 Offshore Submerged Reef Breakwater

An offshore, submerged broad-crested breakwater will lessen the wave energy reaching the shoreline significantly. The reef breakwater will be made of discarded oyster shells, which are a local recycled material and provide a great substrate for oyster spat settlement and possible oyster reef creation. The primary benefit of the reef breakwater is the lessening of wave energy by causing waves to break and dissipate much of their energy in turbulence before reaching shore. This will allow for the sea grasses and intertidal grasses to have a suitable environment for colonization while protecting the berm from large wave events. The possibility of oyster reef creation will be another ancillary benefit because oysters can greatly improve the water quality of an area (Stout, 1998). This is not the primary objective of the breakwater and should not be looked to as such. The breakwater will also provide habitat for fauna other than oysters. This essential habitat would lead to an overall healthier nekton population, large and small fish, being present in the area and when this happens bird and human fisherman are sure to follow. Therefore the design will benefit birds of prey as well as the local human population by producing a fishing ground. The presence of sport fisherman in the area will be a great way to passively educate the public about alternative shoreline protection plans. It can also be assumed that they would probably approve this type of erosion mitigation plan since they are reaping the benefits of it by fishing in the area.

In order for shoreline plantings of *Spartina alterniflora* to be successful, a rule of thumb is that significant wave heights of less than one foot are necessary (Roland and Douglass, 2005). It was also noted by Roland and Douglass that 80 percentile significant wave height should be at most equal to 0.2 meters (0.656 feet). Therefore the reef breakwater should decrease almost all wave heights to less than one foot in the study area, while transforming the 80 percentile significant wave height to 0.2 meters. Guidance in determining the wave transmission for the reef was provided by *Wave transmission and reflection at low-crested structures: Design formulae, oblique wave attack and spectral change* by Van der Meer et. al (2005). The study used a new database of more than 2300 tests to determine the best two dimensional wave transmission formula of rubble mound low-crested structures. An important factor in the design of low crested structures is the relative crest width, which is the crest width of the structure divided by the height of the design wave impacting the shoreline. It was determined that for structures with a relative crest width of less than 10 the d'Angremond et al. (1996) formula is preferable. The d'Angremond formula reads

$$K_t = -0.4\frac{R_c}{H_i} + 0.64\left(\frac{B}{H_i}\right)^{-0.31}\left(1 - e^{-0.5\xi}\right) \tag{5-1}$$

In this formula, K_t is wave transmission, R_c is the reef crest freeboard, H_i is the significant incident wave height, B is the width of reef crest, and ξ is surf similarity parameter. This formula was implemented in a spreadsheet to compute the dimensions of the reef breakwater which would lessen the wave height to a level which shoreline vegetation can grow. According to the wave climate analysis previously performed in this study, it was determined that the 80 percentile significant wave height is very close but slightly larger than 0.2 meters. Since so little change is needed in the 80 percentile wave, large significant wave heights in the 99 percentile are the controlling factor in breakwater design. The dimensions of the breakwater are then used to compute the volume of shell needed per unit length for this breakwater and also the area per unit length of the footprint of the breakwater. These measurements are coupled with cost estimates provided by the Mississippi Alabama Sea Grant Program (MASGP) in the paper *Shoreline Protection Product* in order to provide an idea of the cost of this project (MASGP, 2007). The highest given cost was used for the cost estimates. The following table presents the method and dimensions which were found to sufficiently attenuate wave energy in the 99 and 80 percentile wave climates.

Table 5.1 Breakwater Crest Dimension Determination (**Based on Van der Meer 2005)**

Variables		**Metric (m)**	**English (ft)**
Incident Wave Height	**H_i**	0.762	2.5
Slope of Breakwater	**tan(α)**	0.3333	0.3333
Peak Period (s)	**T_p**	3.6	3.6
Gravity	**g**	9.81	32.2
Surf Similiarity Parameter	**ξop**	1.718	1.718
Water Depth	**d**	1.1	3.61
Freeboard	**R_c**	-0.1	-0.33
Relative Freeboard	**R_c/H_i**	-0.131	-0.131
Reef Height	**$h=d-R_c$**	1	3.28
Crest Width	**B**	6	19.69
Relative Crest Width	**B/H_i**	7.874	7.874
Solutions		**if (B/Hi)>10**	**if (B/Hi)<10**
Wave Transmission Coefficient	**K_t**	0.1133	0.2470
		Metric (m)	**Metric (m)**
Incident Wave Height after Breakwater	**H_f**	0.09	0.19
		English ft)	**English ft)**
		0.28	0.62

		m^3/m	ft^3/ft	yd^3/yd
Volume of Shell Needed=	$\mathbf{V_{shell}}$	9	96.9	10.77
Area of Footprint	**A**	12	39.4	4.38

Cost of Oyster Shell @ $45-$55/yd^3	per linear foot		$592.27
Cost of Geotextile @ $0.70-1.35/$yd^2$	per linear foot		$5.91
Total Cost of Oyster Reef Breakwater	per linear foot		$598.18

Other studies are being performed to better estimate the wave transmission behind low crested structures. One such project is using artificial neural network models to estimate the transmission (Panizzo and Briganti, 2007). The dimensions of the reef, as determined by the d'Angremond formula, were checked against this method in the spirit of tiered analysis and checking solutions. This was easily done as an internet friendly version of the transmission calculator based on artificial neural networks is found on the web page http://w3.uniroma1.it/cmar/wave_transm_kt.htm. Similar and satisfactory results were obtained giving added confidence in that the dimensions are acceptable.

The oyster reef breakwater system for the 0.63 miles of shoreline will cost between eight hundred thousand and one million dollars, if only oyster shells are used to build the breakwaters. But if riprap is primarily used for the construction of the breakwaters and oyster shells are used to coat the structure, the cost could be lowered to between six hundred and fifty thousand to three hundred and fifty thousand dollars. The breakwater will have a crest width of 6 meters and will be submerged 0.1 meters below mean tide level. The breakwater will continue to achieve the needed wave height reduction if the crest is submerged 0.3 meters below sea level. This was done to protect against localized water level rise and eustatic sea level rise. The current global average rate of sea rise has been about 3 millimeters per year and the latest report by the International Panel on Climate Change give projections of 0.21-0.48 m by the end of the century (Gregory, 2008). At this high rate, the breakwater will continue to shelter the shoreline from high waves for 50-100 years. This time frame is considered to be the lifetime for which the breakwaters will lessen shoreline erosion. The uncertainty about the future height of sea level is the limiting variable in the useful lifetime of the breakwater.

Another feature of the reef breakwater which allows it to be submerged as well as diminish energy from large waves to an acceptable level as they pass over is a very broad crest. It will also be set 15 meters offshore at mean tide level. This distance from the shoreline plus the width of the breakwater corresponds with the largest depth of closure estimate for the study area. The breakwater will be segmented into many different sections along the shoreline, in order to allow circulation and flushing and prevent excessive scour around the ends of breakwater. Most breakwaters will be 10 meters in length with a gap of 10 meters between the breakwaters. They will also be tapered at the ends of the study area to lessen their effects on the longshore transport up and down the shoreline. The design guidance for the sizing and spacing of breakwaters was provided by the CEM as well as Coastal Engineering Technical Note III-43, *Empirical methods for the functional design of detached breakwaters for shoreline stabilization.* These calculations are presented in Table 5.2.

Table 5.2 Breakwater Spacing

Variables			
Breakwater distance from shoreline	Y_b	15	m
Length of breakwater	L_b	10	m
Length of gap	L_g	10	m

Parameters for Salient Formation	
if $L_g*Y_b / L_b^2 > 0.5$, tombolos will not form	1.5
if $L_g/Y_b < 0.8$ no erosion will occur in gaps	0.666667
if L_b/Y_b=0.5-0.67, salients will form	0.666667
if $Y_b/L_b < 1$ yields tombolo formation	1.5

It is important and responsible to remember not to exacerbate erosion problems in nearby areas. If sediment accumulation does occur in this area, it will not be devastating to the surrounding area because relatively little sediment could be trapped between the breakwater and shoreline. If this situation occurred, sediment would bypass the study area and once again supply sediment up and down the shoreline. In this manner, this design is a responsible and sedimentologically aware solution to the shoreline erosion issues occurring at the site.

This shoreline erosion mitigation design has many benefits including: lessening wave energy reaching the shoreline, improving the overall health of the ecosystem in the area, protecting the shoreline and landward areas from high winds and storm surges, and even increasing the aesthetic appeal of the shoreline. It is a plan which uses native plants and local, non-toxic, previously used material which create ancillary environmental and economical benefits for the study site as well as the general area.

CHAPTER 6

CONCLUSIONS

Mobile Bay is a classic example of a submerged river valley estuary and acts as the receiving waters for the sixth largest river system in the United States (Stout, 1998). Estuaries of this type are the product of the sea level rise which has been occurring since the end of the last glacial epoch and the beginning of the Holocene Epoch. Estuaries of this type have a natural tendency to become very wide and shallow. This morphological process is assisted when sediment from the shoreline is mobilized and transported to the bay bottom. This has the effect of moving the shoreline landward, widening the bay, and depositing material, thereby raising the bed elevation. Other processes, such as deposition from rivers are important, but since this is a discussion about shoreline erosion it will not be discussed. The bay's morphological tendencies were considered in analyzing the erosional processes around this shoreline and determining suitable erosion mitigation strategies at the site. This concept makes it apparent that drawing an arbitrary line on the shoreline in which to fortify and deeming that the permanent shoreline would be a very unwise decision. In order to legitimately protect the shoreline, the area must be prepared to make healthy changes and transitions, which will help prevent a large erosional episode removing land and moving the shoreline a great deal while depositing a large amount of sediment in the bay.

It was found that the erosional processes being experienced by this beach/berm/wetland system in Southeast Mobile Bay are influenced and forced by a variety of local and regional processes. The dynamic and complex environment found in estuarine systems coupled with the inherent uncertainties in sediment transport quantification made this project interesting, complex, and informational. Wave energy introduced by wind and ship traffic is probably the largest contributor to erosional processes occurring along the beach. The longshore transport of sediment is generally bi-directional with dominant transport from the North to South. Large waves associated with high wind speeds also affect the shoreline negatively by eroding sediment from the shoreline. Also negatively affecting the project area is an area of shoreline north of the shoreline but south of the inlet to Weeks Bay which is heavily fortified with bulkheads. It has been noted that these structures tend to pass along erosion problems adjacent shorelines (Douglass and Pickel, 1999). Episodic extreme meteorological events, i.e. hurricanes, are also a force contributing to the evolution of the beach.

This shoreline and berm is gradually receding into the intermittent freshwater wetland located behind the berm and perched above the Bay. This particular area is anchored at the northern end by a headland of trees, shrubs, and grasses. While this is not the typical rocky outcrop type of headland, it is still functioning in the same manner by helping create a cuspate shape beach which can be noticed in Figure 3.10. Without a shoreline protection scheme, the shoreline would continue to recede in the cuspate fashion until the vegetated headland is under- or back-cut and lost. That will create a pulse of sediment in area and the shoreline would continue to erode in phase. Another erosional process, which was prevalent in the area, was scarp erosion of established root mats of *Spartina patens*. The root mats are very resilient to erosion but their weakness is in the area of the intertidal zone which is too low for *patems* to grow. This process is significant as it not only erodes and affects a section of shoreline but undermines the natural protection scheme for this shoreline and puts the entire shoreline and freshwater wetland at risk of a massive erosion event associated with extreme episodic events.

In analyzing the project area, it was found that longshore transport is bi-directional with the dominant direction of sediment transport being from the North to the South. This is probably the trend caused by winter weather patterns. It is most likely that sediment is transported from South to North in the summer because of the predominantly southerly winds. Ship waves propagating from the main channel of Mobile Bay also act to move sediment from North to South because of the orientation of the shoreline.

Cross-shore, as well as longshore, transport is very important to this project. In fact, they are both invented segmentations of the actual total transport flux, which is what is truly important. The segmentations make the flux easier to determine and discuss. This way of looking at the transport is helpful is determining which processes are dominating the evolution of the shoreline. It was determined that cross-shore transport has a very destructive effect on the shoreline during periods of high wave height. Sediment begins to be transported offshore when winds reach 7 m/s. The majority of offshore transport occurs at wind speeds between 7 and 12 m/s. The larger wind speed will contribute much more erosion per unit time of occurrence but those occurrences are much rarer. An erosion control system which lessens wave energy reaching the beach is necessary so that excessive sediment will not be suspended and transported out in the Bay.

In order to adequately address the forcings of sediment transport in the study area and prepare the beach/berm/wetland system for healthy shoreline migration, a variety of environmental responsible erosion mitigation ideas were considered for the design. The design plan includes:

- Wetland and berm planting of trees and shrubs
- Fortification of shoreline by intertidal plantings throughout the surf zone
- Submerged aquatic vegetation establishment
- Submerged offshore broad-crested reef breakwater

Vegetative plantings were a large part of the erosion control concepts discussed. Trees and shrubs will be planted along the back of the berm and in the freshwater wetland behind the berm. These large woody plants will stabilize soil and vegetation in the area. They will create habitat for local fauna and a shady microclimate for other flora. They will also lessen storm surge in the extreme meteorological events and “lift” winds thereby protecting the area landward from strong straight line winds coming from the bay. This is caused by the nature of the successive plantings at different heights. The grasses are close to the ground on the beach and berm, the shrubs are medium height plants on the berm and backside of the berm, and the taller trees are on the back side of the berm and in the wetland. This arrangement progressively lifts winds up and over the landward area. Protection of the shoreline and swash zone will be accomplished by transitioning from trees and shrubs into berm and intertidal grasses. These grasses will protect the shoreline while providing habitat for small fishes and invertebrates. Several different species will be used in order to ensure protection over the entire tidal range and during extreme high and low water levels. Below the intertidal grasses, submerged aquatic vegetation will also be planted. These sea grasses will help prevent the shoreline plant communities from failing by scarp erosion. The sea grasses will colonize and fortify the bottom area which is too deep for emergent grasses (i.e. *Spartina alterniflora*). All of these vegetative plantings will be protected from excessive wave energy by a low-crested reef breakwater. The breakwater can be made from discarded oyster shells, which are inexpensive, previously used, and local materials. This will decrease project cost as well as providing a suitable substrate for the settlement of oyster spat. If an oyster reef begins to form, then the oyster reef breakwater will not only provide a wave damping effect for the shoreline, but will also provide considerable water quality benefits. NOAA bathymetric charts which show historical oyster reefs in the area make this possibility particularly interesting. By using a meld of these technologies, a shoreline erosion mitigation plan will be implemented which provides many benefits and is compatible with the surrounding environment.

Shoreline erosion is a complicated problem with many variables. It is therefore necessary to implement design plan which addresses many different issues and erosional forcings occurring on the beach/berm/wetland system. Environmentally responsible erosion mitigation techniques which will protect the shoreline sediment and ecological integrity of the area are available. These ideas and concepts should be implemented in order that shorelines and estuaries can be protected and improved in a productive manner. A design plan which includes these concepts and ideas will mitigate erosion and create a more beautiful, more productive, and healthier shoreline.

Other research could be performed in the area on the affect of the shielding by Dauphin Island for the Dauphin Island Anemometer, which is Station DPIA1. The anemometer, which is maintained by the National Buoy Data Center, is located off the eastern end of Dauphin Island at 30° 14' 54" N, 88° 04' 24" W. The island could be acting to shield the anemometer from westerly winds. The island does not completely shield the anemometer from all winds, and the westerly winds could be read as being much lower than true speed by this anemometer. The surface roughness of the island with its houses and trees could be acting to slow down winds moving across the islands. Only the western winds would be affected because of the location of anemometer. Winds from the other directions will be unaffected by land masses immediately adjacent to the anemometer, as the closest one is Fort Morgan at just under 5 kilometers to the east. This research idea was discovered during wave climate analysis and noticing high western wind speeds being infrequent. Research into quantifying the affect of Dauphin Island on westerly wind readings is necessary. This would improve the basis for all models reliant upon this wind gauge, particularly wave climate models and hydrodynamic models of the bay.

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APPENDIX

WIND SPEED FREQUENCY ANALYSIS TABLES

A. Wind Speed Frequency Analysis Tables

Occurrence Frequency		Wind Direction					
		0-9	10-19	20-29	30-39	40-49	50-59
Wind Speed	0	119	23	26	31	33	27
	1	253	273	256	258	242	253
	2	458	490	529	520	446	402
	3	681	700	658	653	631	587
	4	854	872	784	712	718	844
	5	876	848	700	646	624	795
	6	922	884	730	632	686	888
	7	940	803	598	534	506	635
	8	886	750	570	421	382	535
	9	765	564	387	284	224	332
	10	524	379	267	143	123	153
	11	377	285	156	85	63	72
	12	252	184	73	29	31	32
	13	181	103	43	23	10	17
	14	96	53	23	7	5	10
	15	41	25	6	3	3	3
	16	18	8	2	2	3	0
	17	6	5	5	1	0	2
	18	2	3	1	0	0	1
	19	0	3	0	0	0	0
	20	1	0	1	1	0	1
	21	1	0	0	0	0	0
	22	2	0	0	0	0	0
	23	1	0	0	0	0	0
	24	0	0	0	0	0	0
	25	0	0	0	0	0	0
	26	0	0	0	0	0	0
	27	0	0	0	0	0	0
	28	0	0	0	0	0	0
	29	0	0	0	0	0	0
	30	0	0	0	0	0	0
TOTAL		8256	7255	5815	4985	4730	5589
Percentage		4.794397	4.2131	3.376868	2.894873	2.74679	3.245626
Σ Percentage		4.794397	9.007497	12.38436	15.27924	18.02603	21.27165

Occurrence Frequency		Wind Direction					
		60-69	70-79	80-89	90-99	100-109	110-119
Wind Speed	0	26	31	25	26	24	12
	1	205	232	239	211	166	198
	2	331	342	327	310	299	333
	3	558	491	417	374	331	380
	4	763	667	553	444	472	582
	5	842	678	520	451	609	831
	6	1017	758	420	509	774	1088
	7	821	601	273	495	803	1006
	8	690	398	217	439	702	733
	9	398	196	115	269	397	437
	10	179	101	76	203	222	215
	11	74	50	49	127	127	125
	12	29	32	24	75	60	47
	13	14	17	14	44	34	33
	14	9	10	7	19	22	13
	15	1	4	5	5	12	12
	16	1	1	3	6	7	3
	17	1	0	1	1	4	2
	18	1	1	0	1	1	2
	19	2	0	1	1	1	0
	20	0	0	0	1	1	4
	21		0	0	1	0	1
	22	1	0	3	0	0	1
	23	0	1	0	1	0	0
	24	2	0	0	0	0	0
	25	1	0	0	0	1	0
	26	0	2	0	0	1	0
	27	0	0	0	0	0	0
	28	1	0	0	0	0	0
	29	0	0	0	0	0	0
	30	0	0	0	0	0	2
TOTAL		5967	4613	3289	4013	5070	6060
Percentage		3.465137	2.678846	1.909977	2.330416	2.944234	3.519143
Σ Percentage		24.73679	27.41564	29.32561	31.65603	34.60026	38.11941

Occurrence Frequency		Wind Direction					
		120-129	130-139	140-149	150-159	160-169	170-179
Wind Speed	0	23	24	23	15	16	19
	1	217	211	207	159	158	161
	2	350	427	527	533	509	514
	3	523	649	748	782	811	1018
	4	842	945	861	880	911	984
	5	1109	1051	991	820	809	789
	6	1291	1069	870	719	637	557
	7	1002	793	617	486	352	334
	8	741	618	258	347	286	204
	9	400	323	258	171	133	106
	10	215	166	106	106	69	53
	11	99	115	75	61	31	31
	12	67	59	51	30	22	15
	13	39	29	33	20	5	7
	14	25	30	9	11	5	5
	15	12	15	11	14	2	6
	16	10	7	6	6	1	2
	17	5	6	2	1	0	3
	18	4	2	4	4	1	0
	19	4	1	1	0	0	2
	20	3	2	0	1	0	0
	21	0	1	0	1	0	2
	22	0	0	0	0	1	0
	23	0	0	0	1	0	0
	24	1	0	0	1	0	0
	25	0	0	0	0	0	0
	26	0	0	1	0	0	0
	27	0	0	0	0	0	1
	28	0	0	1	1	0	0
	29	0	0	0	0	0	0
	30	1	0	0	0	0	0
TOTAL		6983	6543	5660	5170	4759	4813
Percentage		4.055145	3.79963	3.286857	3.002305	2.763631	2.79499
Σ Percentage		42.17455	45.97418	49.26104	52.26334	55.02697	57.82196

Occurrence Frequency		Wind Direction					
		180-189	190-199	200-209	210-219	220-229	230-239
Wind Speed	0	11	18	19	20	16	19
	1	158	197	217	236	234	266
	2	581	768	738	641	531	555
	3	1189	1286	1341	1273	960	817
	4	1131	1082	1139	1463	1291	973
	5	760	646	695	977	1181	877
	6	504	388	346	525	633	619
	7	279	170	132	211	267	281
	8	143	59	52	70	81	68
	9	69	35	19	18	22	33
	10	44	16	7	9	12	13
	11	19	4	6	6	3	9
	12	10	7	6	2	1	3
	13	6	4	0	0	0	0
	14	4	0	1	0	0	0
	15	3	0	0	0	0	0
	16	2	0	0	0	0	0
	17	2	0	0	0	0	0
	18	2	0	0	0	0	0
	19	1	0	0	0	0	0
	20	1	0	0	0	0	0
	21	1	0	0	0	0	0
	22	0	0	0	0	0	0
	23	0	0	0	0	0	0
	24	0	0	0	0	0	0
	25	0	0	0	0	0	0
	26	0	0	0	0	0	0
	27	0	0	0	0	0	0
	28	0	0	0	0	0	0
	29	0	0	0	0	0	0
	30	0	0	0	0	0	0
TOTAL		4920	4680	4718	5451	5232	4533
Percentage		2.857126	2.717754	2.739821	3.165487	3.03831	2.632389
Σ Percentage		60.67909	63.39684	66.13667	69.30215	72.34046	74.97285

Occurrence Frequency		Wind Direction					
		240-249	**250-259**	**260-269**	**270-279**	**280-289**	**290-299**
Wind Speed	**0**	15	18	14	29	26	22
	1	240	229	180	227	207	221
	2	688	734	663	472	371	373
	3	1043	1022	832	503	457	438
	4	842	655	487	394	427	513
	5	625	446	301	274	396	463
	6	422	265	188	211	324	338
	7	197	116	69	109	170	204
	8	71	54	40	78	109	177
	9	33	24	22	37	53	109
	10	10	8	17	17	34	77
	11	5	3	7	10	32	57
	12	6	1	0	4	16	36
	13	1	0	0	7	9	16
	14	0	0	0	1	3	12
	15	0	0	0	0	5	3
	16	0	0	0	0	2	3
	17	0	0	0	0	1	2
	18	0	0	0	0	1	1
	19	0	0	0	0	0	2
	20	0	0	0	0	0	1
	21	0	0	0	0	0	0
	22	0	0	0	0	0	1
	23	0	0	0	0	0	0
	24	0	0	0	0	0	0
	25	0	0	0	0	0	0
	26	0	0	0	0	0	0
	27	0	0	0	0	0	0
	28	0	0	0	0	0	0
	29	0	0	0	0	0	0
	30	0	0	0	0	0	0
TOTAL		4198	3575	2820	2373	2643	3069
Percentage		2.437849	2.076062	1.637621	1.378041	1.534834	1.78222
Σ Percentage		77.4107	79.48676	81.12438	82.50242	84.03726	85.81948

Occurrence Frequency		Wind Direction					
		300-309	310-319	320-329	330-339	340-349	350-360
Wind Speed	0	28	28	23	28	20	26
	1	198	200	172	220	213	221
	2	309	287	327	334	259	367
	3	376	346	385	402	434	499
	4	421	396	428	417	472	606
	5	397	379	383	423	479	608
	6	348	361	404	493	509	633
	7	265	302	379	440	462	574
	8	215	349	400	484	447	594
	9	166	237	287	367	341	439
	10	104	176	211	258	241	334
	11	90	116	132	198	211	262
	12	53	94	78	122	147	194
	13	39	38	51	57	94	108
	14	20	23	28	31	33	68
	15	10	9	18	16	18	44
	16	3	7	4	3	10	17
	17	3	3	6	0	2	6
	18	2	0	2	0	0	0
	19	1	1	2	0	1	0
	20	3	1	0	1	0	0
	21	2	0	1	0	1	0
	22	0	0	0	0	0	0
	23	0	0	0	0	1	0
	24	0	0	0	0	0	0
	25	1	0	0	0	0	0
	26	0	0	0	1	0	0
	27	0	0	1	0	0	0
	28	0	0	0	0	0	0
	29	0	0	0	0	0	0
	30	0	0	0	0	0	0
TOTAL		3054	3353	3722	4295	4395	5600
Percentage		1.773509	1.947143	2.161428	2.494178	2.55225	3.252014
Σ Percentage		87.59299	89.54013	91.70156	94.19574	96.74799	100

Occurrence Frequency		Total	Percentage	Running Total of Percentages
Wind Speed	**0**	903	0.524387199	0.524387199
	1	7735	4.491843834	5.016231032
	2	16645	9.666029814	14.68226085
	3	24595	14.28272774	28.96498859
	4	26825	15.57772603	44.54271462
	5	24299	14.11083559	58.65355021
	6	21962	12.75370062	71.40725083
	7	16226	9.422709508	80.82996034
	8	12668	7.356519416	88.18647975
	9	8070	4.686383935	92.87286369
	10	4888	2.83854333	95.71140702
	11	3172	1.842033438	97.55344046
	12	1892	1.098716035	98.65215649
	13	1096	0.636465526	99.28862202
	14	583	0.338557848	99.62717987
	15	306	0.177699316	99.80487918
	16	137	0.079558191	99.88443737
	17	70	0.04065017	99.92508754
	18	36	0.020905802	99.94599334
	19	24	0.013937201	99.95993055
	20	23	0.013356485	99.97328703
	21	12	0.006968601	99.98025563
	22	9	0.00522645	99.98548208
	23	5	0.002903584	99.98838567
	24	4	0.002322867	99.99070853
	25	3	0.00174215	99.99245068
	26	5	0.002903584	99.99535427
	27	2	0.001161433	99.9965157
	28	3	0.00174215	99.99825785
	29	0	0	99.99825785
	30	3	0.00174215	100

APPENDIX B
SIGNIFICANT WAVE HEIGHT TABLES

B. Significant Wave Height Tables

Significant Wave Height in Feet

Significant Wave Height		Wind Direction						
		130-139	140-149	150-159	160-169	170-179	180-189	190-199
	1	0.03	0.03	0.03	0.03	0.03	0.03	0.03
	2	0.12	0.13	0.13	0.13	0.13	0.13	0.13
	3	0.23	0.25	0.25	0.25	0.25	0.25	0.26
	4	0.32	0.36	0.37	0.37	0.37	0.37	0.38
	5	0.41	0.47	0.48	0.49	0.49	0.49	0.50
	6	0.49	0.58	0.59	0.60	0.60	0.61	0.62
	7	0.56	0.68	0.69	0.71	0.71	0.72	0.74
	8	0.63	0.78	0.79	0.81	0.82	0.83	0.85
	9	0.69	0.88	0.89	0.92	0.92	0.94	0.96
Wind	10	0.75	0.97	0.98	1.01	1.02	1.04	1.06
Speed	11	0.81	1.05	1.06	1.10	1.12	1.14	1.16
	12	0.86	1.14	1.14	1.19	1.21	1.24	1.25
	13	0.91	1.22	1.23	1.28	1.30	1.33	1.35
	14	0.96	1.29	1.30	1.36	1.39	1.42	1.44
	15	1.01	1.37	1.38	1.45	1.47	1.51	1.52
	16	1.05	1.44	1.45	1.52	1.55	1.59	1.61
	17	1.10	1.51	1.52	1.60	1.63	1.67	1.69
	18	1.14	1.58	1.59	1.68	1.71	1.75	1.77
	19	1.18	1.65	1.65	1.75	1.79	1.83	1.85
	20	1.22	1.71	1.72	1.82	1.86	1.91	1.92
	21	1.26	1.78	1.78	1.89	1.93	1.98	2.00
	22	1.30	1.84	1.84	1.95	2.00	2.05	2.07
	23	1.34	1.90	1.90	2.02	2.07	2.13	2.14
	24	1.38	1.96	1.96	2.08	2.14	2.20	2.21
	25	1.41	2.01	2.02	2.15	2.20	2.26	2.27
	26	1.45	2.07	2.08	2.21	2.27	2.33	2.34
	27	1.49	2.13	2.13	2.27	2.33	2.39	2.41
	28	1.52	2.18	2.18	2.33	2.39	2.46	2.47
	29	1.56	2.23	2.24	2.38	2.45	2.52	2.53
	30	1.59	2.29	2.29	2.44	2.51	2.58	2.59

Significant Wave Height **Wind Direction**

		200-209	210-219	220-229	230-239	240-249	250-259	260-269
	1	0.03	0.03	0.03	0.03	0.04	0.04	0.04
	2	0.13	0.13	0.14	0.14	0.17	0.17	0.17
	3	0.26	0.28	0.28	0.29	0.37	0.39	0.39
	4	0.40	0.42	0.43	0.45	0.59	0.63	0.64
	5	0.52	0.56	0.58	0.60	0.80	0.86	0.87
	6	0.64	0.69	0.71	0.75	0.99	1.06	1.08
	7	0.76	0.82	0.85	0.89	1.18	1.25	1.28
	8	0.88	0.95	0.97	1.03	1.35	1.44	1.46
	9	0.99	1.07	1.10	1.17	1.52	1.61	1.64
Wind	10	1.09	1.19	1.22	1.30	1.68	1.77	1.81
Speed	11	1.19	1.31	1.33	1.42	1.84	1.92	1.97
	12	1.29	1.42	1.44	1.55	1.99	2.07	2.12
	13	1.38	1.52	1.55	1.66	2.13	2.21	2.27
	14	1.47	1.62	1.65	1.78	2.27	2.35	2.41
	15	1.55	1.72	1.74	1.89	2.41	2.48	2.55
	16	1.64	1.81	1.84	1.99	2.54	2.60	2.68
	17	1.72	1.90	1.93	2.09	2.67	2.72	2.81
	18	1.80	1.99	2.02	2.19	2.79	2.84	2.93
	19	1.87	2.08	2.10	2.29	2.91	2.96	3.05
	20	1.95	2.16	2.19	2.38	3.02	3.07	3.17
	21	2.02	2.25	2.27	2.47	3.13	3.18	3.28
	22	2.09	2.33	2.35	2.56	3.24	3.28	3.39
	23	2.16	2.40	2.42	2.65	3.34	3.39	3.50
	24	2.23	2.48	2.50	2.73	3.44	3.49	3.61
	25	2.30	2.56	2.57	2.81	3.54	3.58	3.71
	26	2.36	2.63	2.65	2.90	3.64	3.68	3.81
	27	2.42	2.70	2.72	2.98	3.74	3.77	3.90
	28	2.49	2.77	2.79	3.05	3.83	3.86	4.00
	29	2.55	2.84	2.85	3.13	3.92	3.95	4.09
	30	2.61	2.91	2.92	3.20	4.01	4.04	4.18

Significant Wave Height		Wind Direction			
		270-279	280-289	290-299	300-309
	1	0.04	0.04	0.04	0.03
	2	0.17	0.17	0.17	0.13
	3	0.39	0.39	0.39	0.27
	4	0.63	0.63	0.64	0.42
	5	0.85	0.85	0.87	0.55
	6	1.06	1.06	1.08	0.68
	7	1.25	1.25	1.27	0.80
	8	1.43	1.43	1.46	0.92
	9	1.61	1.60	1.63	1.04
Wind	10	1.77	1.77	1.80	1.15
Speed	11	1.92	1.92	1.95	1.26
	12	2.07	2.07	2.10	1.37
	13	2.21	2.21	2.25	1.46
	14	2.34	2.34	2.39	1.56
	15	2.47	2.47	2.52	1.65
	16	2.60	2.60	2.65	1.74
	17	2.72	2.72	2.77	1.82
	18	2.84	2.84	2.89	1.91
	19	2.96	2.96	3.01	1.99
	20	3.07	3.07	3.12	2.07
	21	3.18	3.18	3.23	2.14
	22	3.28	3.28	3.34	2.22
	23	3.39	3.39	3.45	2.29
	24	3.49	3.49	3.55	2.36
	25	3.58	3.58	3.65	2.43
	26	3.68	3.68	3.75	2.50
	27	3.77	3.77	3.84	2.57
	28	3.86	3.86	3.93	2.64
	29	3.95	3.95	4.02	2.70
	30	4.04	4.04	4.11	2.77

APPENDIX C

SIGNIFICANT WAVE PERIOD TABLES

C. Significant Wave Period Tables

Significant Wave Period in Seconds

Significant Wave Period		Wind Direction						
		130-139	140-149	150-159	160-169	170-179	180-189	190-199
	1	0.42	0.42	0.42	0.42	0.42	0.42	0.42
	2	0.81	0.83	0.83	0.83	0.83	0.84	0.84
	3	1.08	1.12	1.13	1.13	1.13	1.14	1.15
	4	1.27	1.34	1.35	1.36	1.36	1.36	1.38
	5	1.42	1.51	1.52	1.53	1.53	1.54	1.56
	6	1.55	1.65	1.67	1.68	1.68	1.69	1.71
	7	1.66	1.78	1.79	1.81	1.81	1.82	1.84
	8	1.76	1.89	1.90	1.92	1.92	1.94	1.96
	9	1.84	1.99	2.00	2.02	2.03	2.04	2.07
Wind	10	1.92	2.08	2.09	2.12	2.12	2.13	2.16
Speed	11	2.00	2.16	2.18	2.20	2.20	2.22	2.25
	12	2.07	2.24	2.26	2.28	2.28	2.30	2.33
	13	2.13	2.31	2.33	2.36	2.36	2.38	2.41
	14	2.20	2.38	2.40	2.43	2.43	2.45	2.48
	15	2.26	2.45	2.47	2.49	2.50	2.52	2.55
	16	2.31	2.51	2.53	2.56	2.56	2.58	2.62
	17	2.37	2.57	2.59	2.62	2.62	2.65	2.68
	18	2.42	2.63	2.65	2.68	2.68	2.71	2.74
	19	2.47	2.68	2.71	2.74	2.74	2.77	2.80
	20	2.51	2.74	2.76	2.79	2.80	2.82	2.86
	21	2.56	2.79	2.81	2.85	2.85	2.88	2.91
	22	2.61	2.84	2.86	2.90	2.90	2.93	2.97
	23	2.65	2.89	2.91	2.95	2.95	2.98	3.02
	24	2.69	2.94	2.96	3.00	3.00	3.03	3.07
	25	2.73	2.98	3.01	3.04	3.05	3.08	3.12
	26	2.77	3.03	3.05	3.09	3.10	3.12	3.16
	27	2.81	3.07	3.10	3.14	3.14	3.17	3.21
	28	2.85	3.12	3.14	3.18	3.19	3.21	3.26
	29	2.89	3.16	3.18	3.22	3.23	3.26	3.30
	30	2.93	3.20	3.22	3.27	3.27	3.30	3.34

Significant Wave Period		Wind Direction						
		200-209	210-219	220-229	230-239	240-249	250-259	260-269
	1	0.42	0.42	0.42	0.42	0.47	0.47	0.47
	2	0.85	0.86	0.87	0.88	0.98	0.99	0.99
	3	1.17	1.20	1.22	1.24	1.40	1.44	1.44
	4	1.41	1.46	1.48	1.51	1.73	1.79	1.80
	5	1.60	1.66	1.69	1.73	2.00	2.08	2.09
	6	1.76	1.83	1.86	1.91	2.22	2.31	2.33
	7	1.89	1.98	2.01	2.07	2.40	2.51	2.53
	8	2.01	2.10	2.14	2.21	2.57	2.69	2.71
	9	2.12	2.22	2.26	2.33	2.71	2.85	2.87
Wind	10	2.22	2.33	2.37	2.44	2.85	2.99	3.01
Speed	11	2.31	2.43	2.47	2.55	2.97	3.12	3.15
	12	2.40	2.52	2.57	2.65	3.09	3.24	3.27
	13	2.48	2.60	2.65	2.74	3.20	3.36	3.38
	14	2.55	2.68	2.73	2.83	3.30	3.46	3.49
	15	2.62	2.76	2.81	2.91	3.40	3.57	3.60
	16	2.69	2.83	2.88	2.98	3.49	3.66	3.69
	17	2.75	2.90	2.95	3.06	3.58	3.75	3.79
	18	2.82	2.96	3.02	3.13	3.66	3.84	3.88
	19	2.88	3.03	3.09	3.19	3.74	3.93	3.96
	20	2.94	3.09	3.15	3.26	3.82	4.01	4.05
	21	2.99	3.15	3.21	3.32	3.89	4.09	4.13
	22	3.05	3.20	3.27	3.38	3.96	4.16	4.20
	23	3.10	3.26	3.32	3.44	4.03	4.24	4.28
	24	3.15	3.31	3.38	3.50	4.10	4.31	4.35
	25	3.20	3.37	3.43	3.55	4.16	4.38	4.42
	26	3.25	3.42	3.48	3.61	4.22	4.44	4.48
	27	3.30	3.47	3.53	3.66	4.29	4.50	4.55
	28	3.34	3.52	3.58	3.71	4.35	4.56	4.61
	29	3.39	3.56	3.63	3.76	4.40	4.62	4.67
	30	3.43	3.61	3.68	3.81	4.46	4.68	4.73

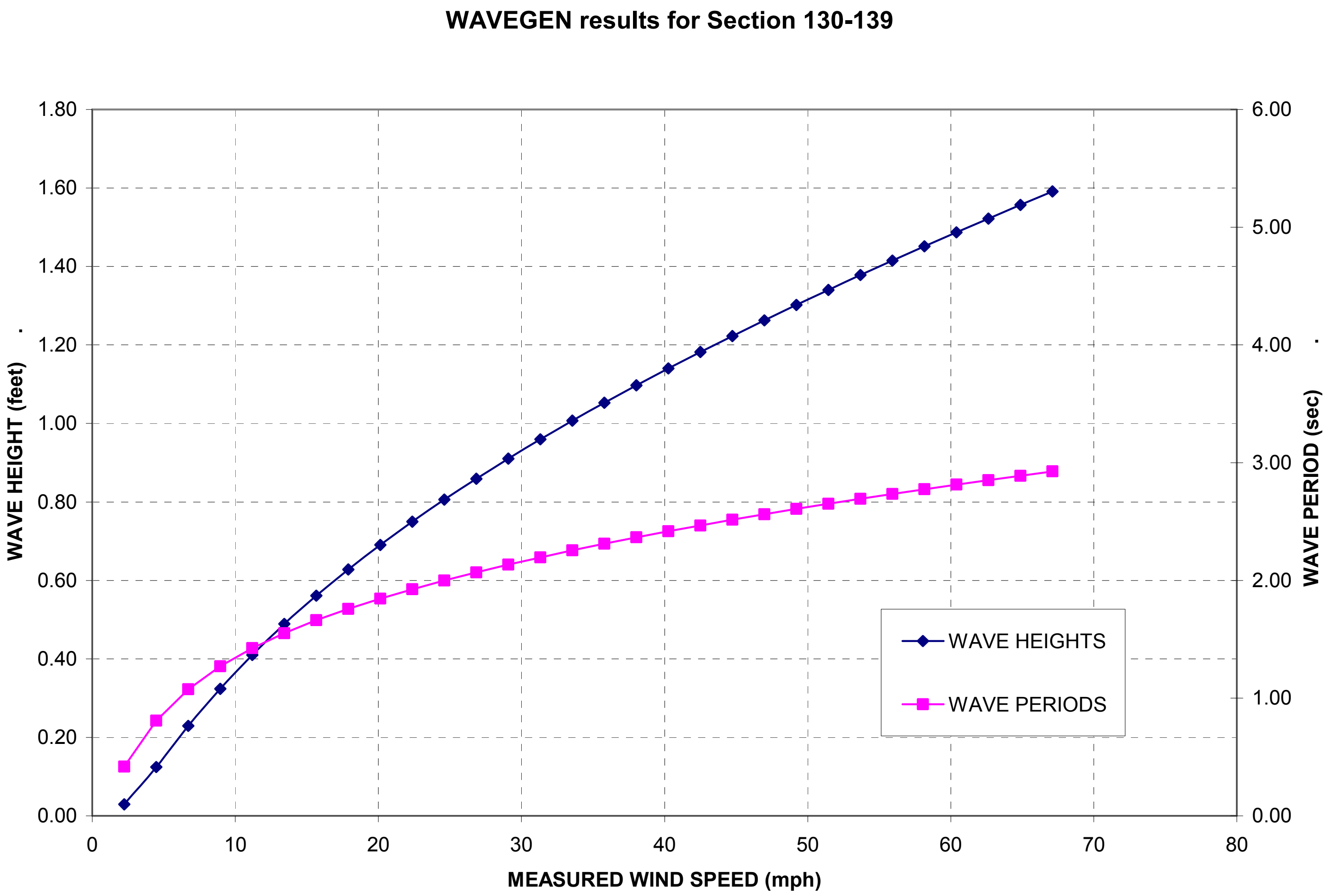
Significant Wave Period

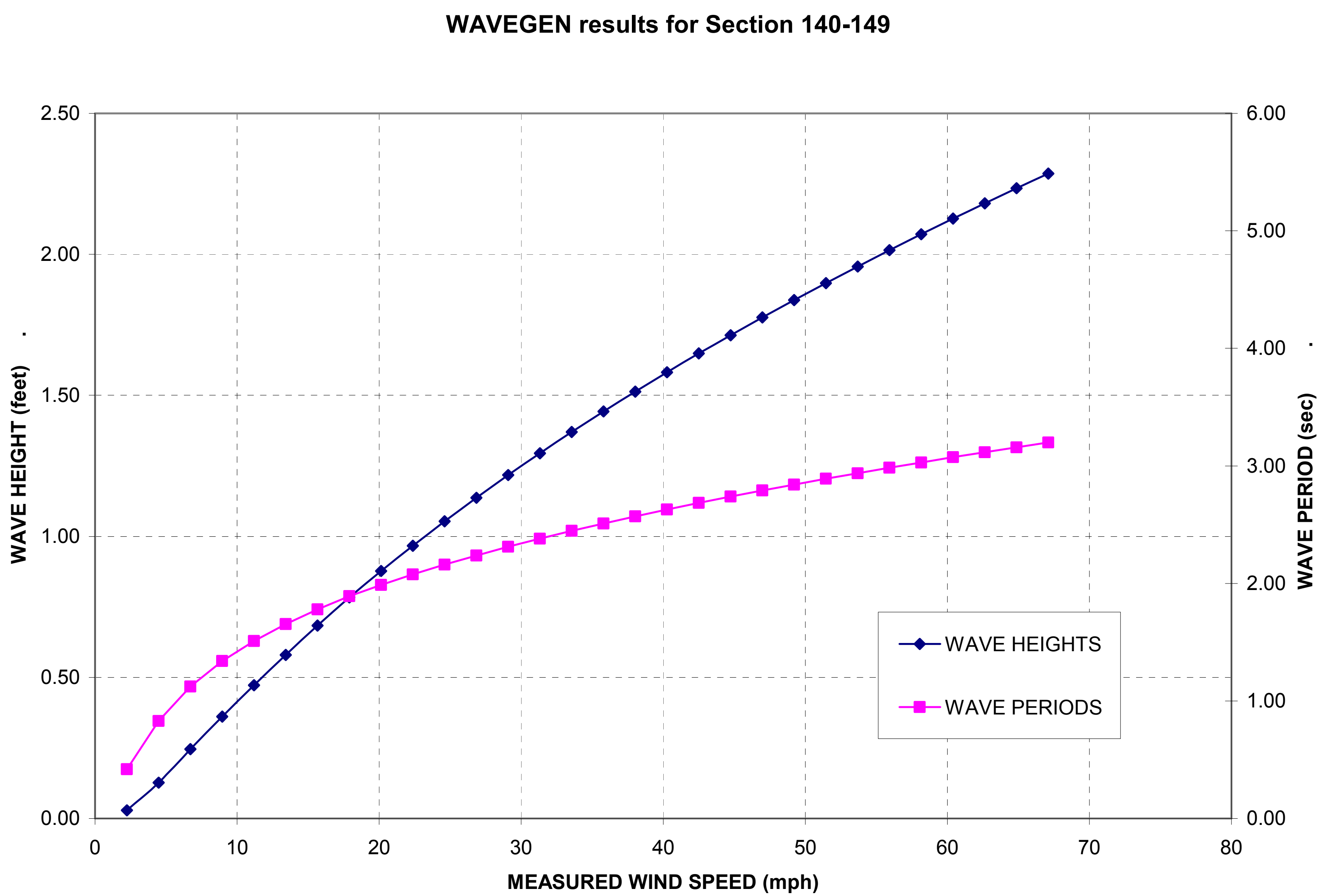
		Wind Direction			
		270-279	**280-289**	**290-299**	**300-309**
	1	0.47	0.47	0.47	0.42
	2	0.99	0.99	0.99	0.86
	3	1.44	1.44	1.45	1.20
	4	1.79	1.79	1.81	1.45
	5	2.08	2.08	2.09	1.64
	6	2.31	2.31	2.33	1.81
	7	2.51	2.51	2.54	1.95
	8	2.69	2.69	2.71	2.08
	9	2.85	2.84	2.87	2.19
Wind	10	2.99	2.99	3.02	2.30
Speed	11	3.12	3.12	3.15	2.39
	12	3.24	3.24	3.27	2.48
	13	3.35	3.35	3.39	2.57
	14	3.46	3.46	3.50	2.64
	15	3.56	3.56	3.60	2.72
	16	3.66	3.66	3.70	2.79
	17	3.75	3.75	3.79	2.85
	18	3.84	3.84	3.88	2.92
	19	3.93	3.92	3.97	2.98
	20	4.01	4.00	4.05	3.04
	21	4.09	4.08	4.13	3.10
	22	4.16	4.16	4.21	3.16
	23	4.24	4.23	4.28	3.21
	24	4.31	4.30	4.35	3.26
	25	4.37	4.37	4.42	3.32
	26	4.44	4.43	4.49	3.37
	27	4.50	4.50	4.55	3.41
	28	4.56	4.56	4.61	3.46
	29	4.62	4.62	4.67	3.51
	30	4.68	4.68	4.73	3.55

APPENDIX D

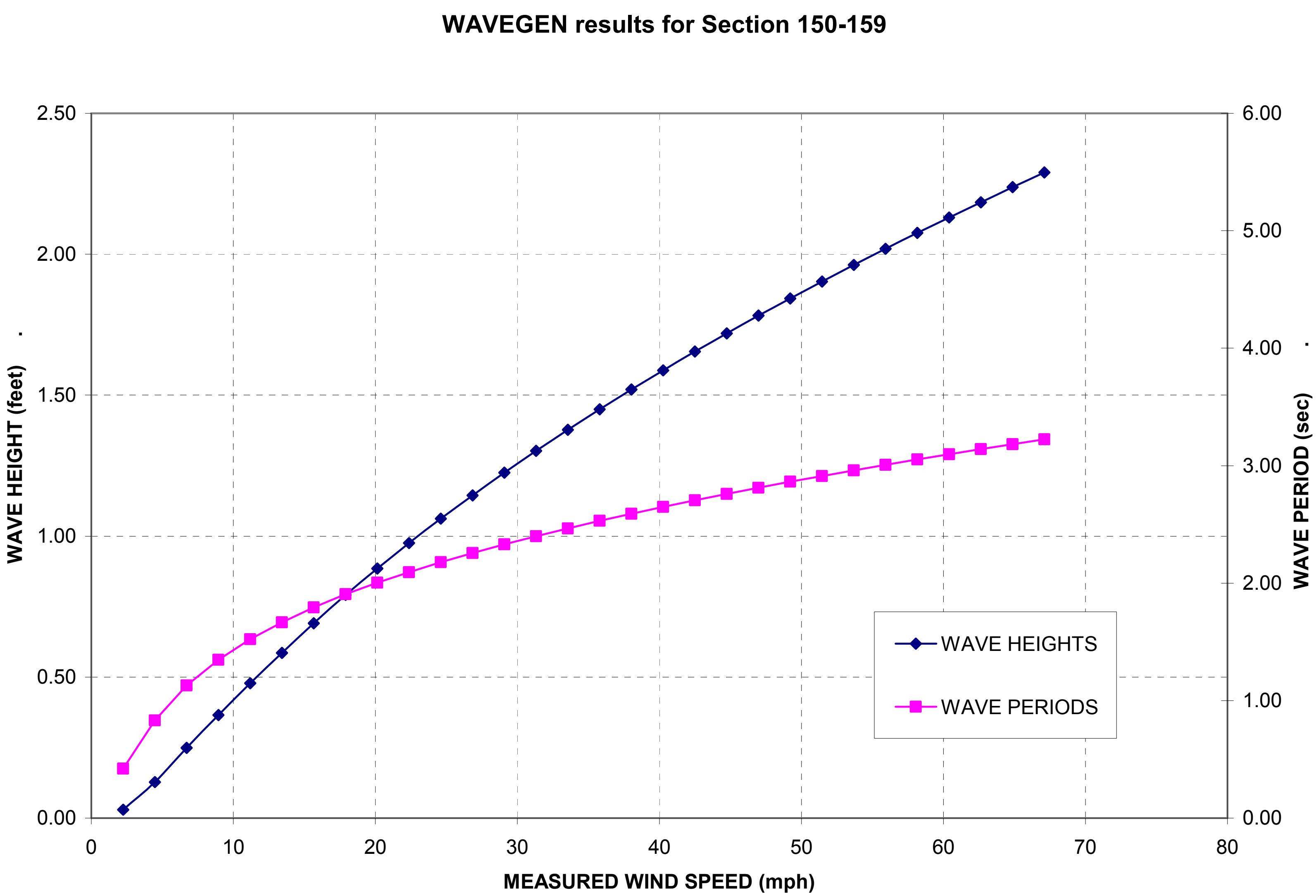
SIGNIFICANT WAVE HEIGHT AND PERIOD GRAPHS

D. Significant Wave Height and Period Graphs

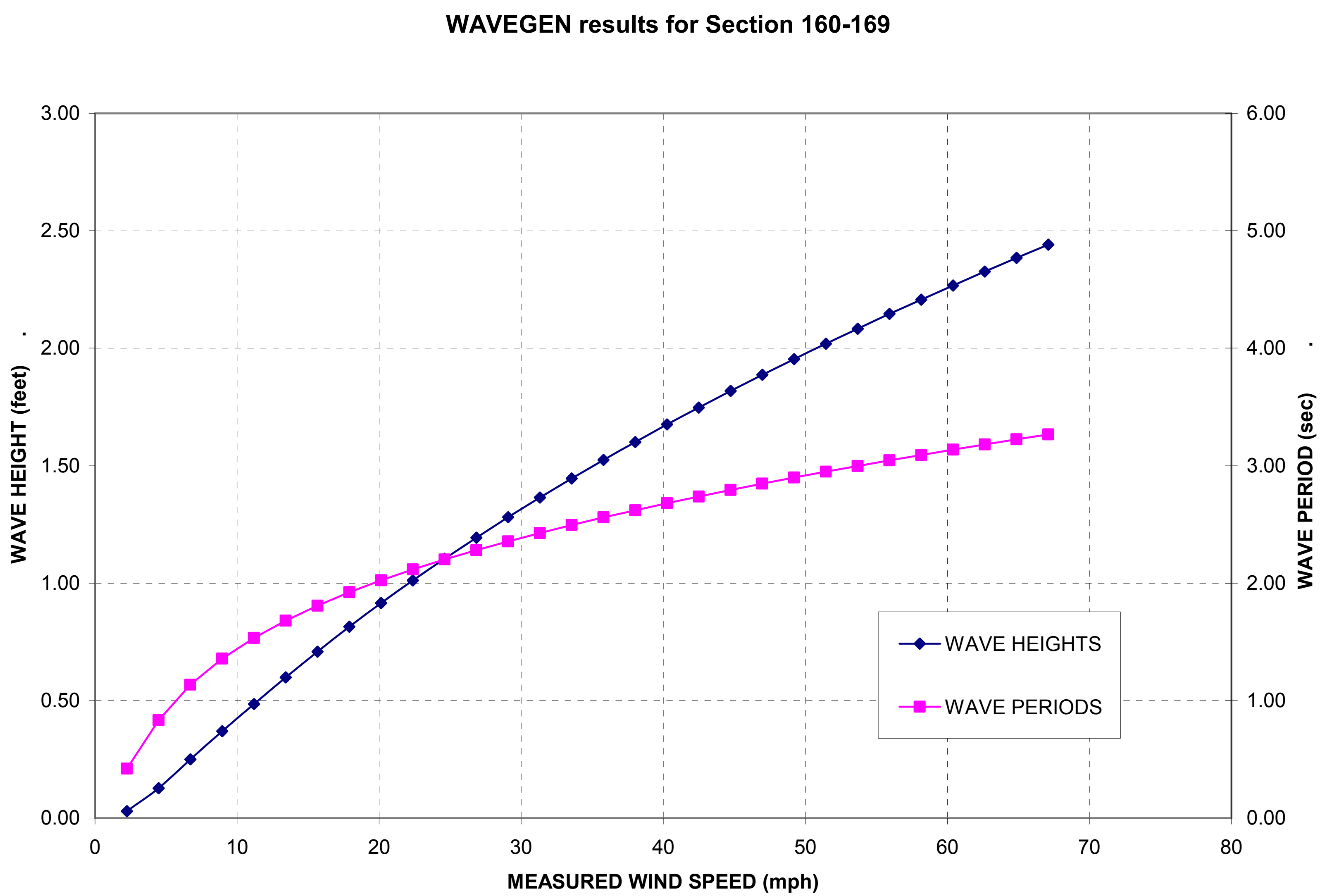


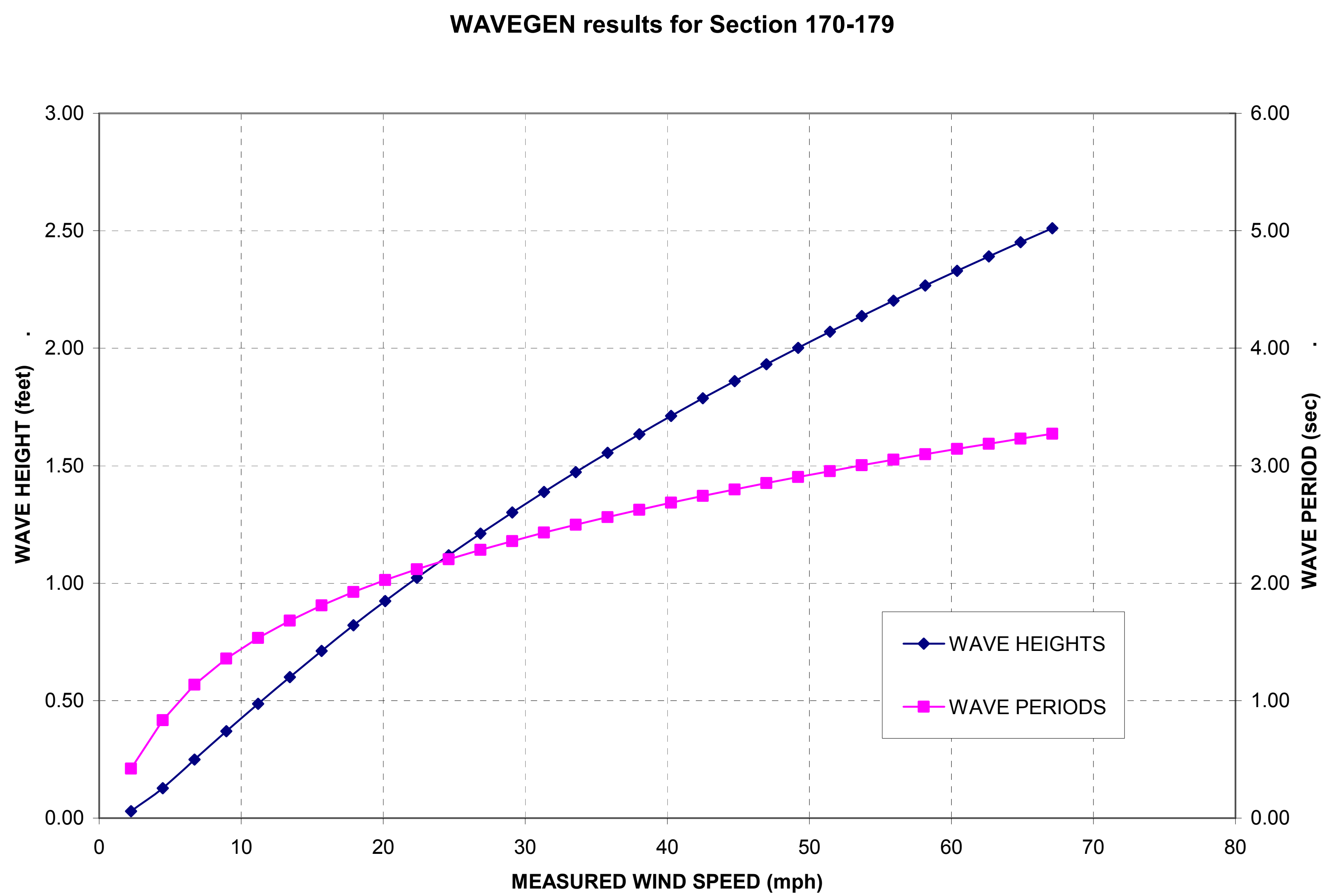


WAVEGEN results for Section 140-149
WAVE HEIGHT (feet)
WAVE PERIOD (sec)
MEASURED WIND SPEED (mph)
WAVE HEIGHTS
WAVE PERIODS
2.50
2.00
1.50
1.00
0.50
0.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0
10
20
30
40
50
60
70
80

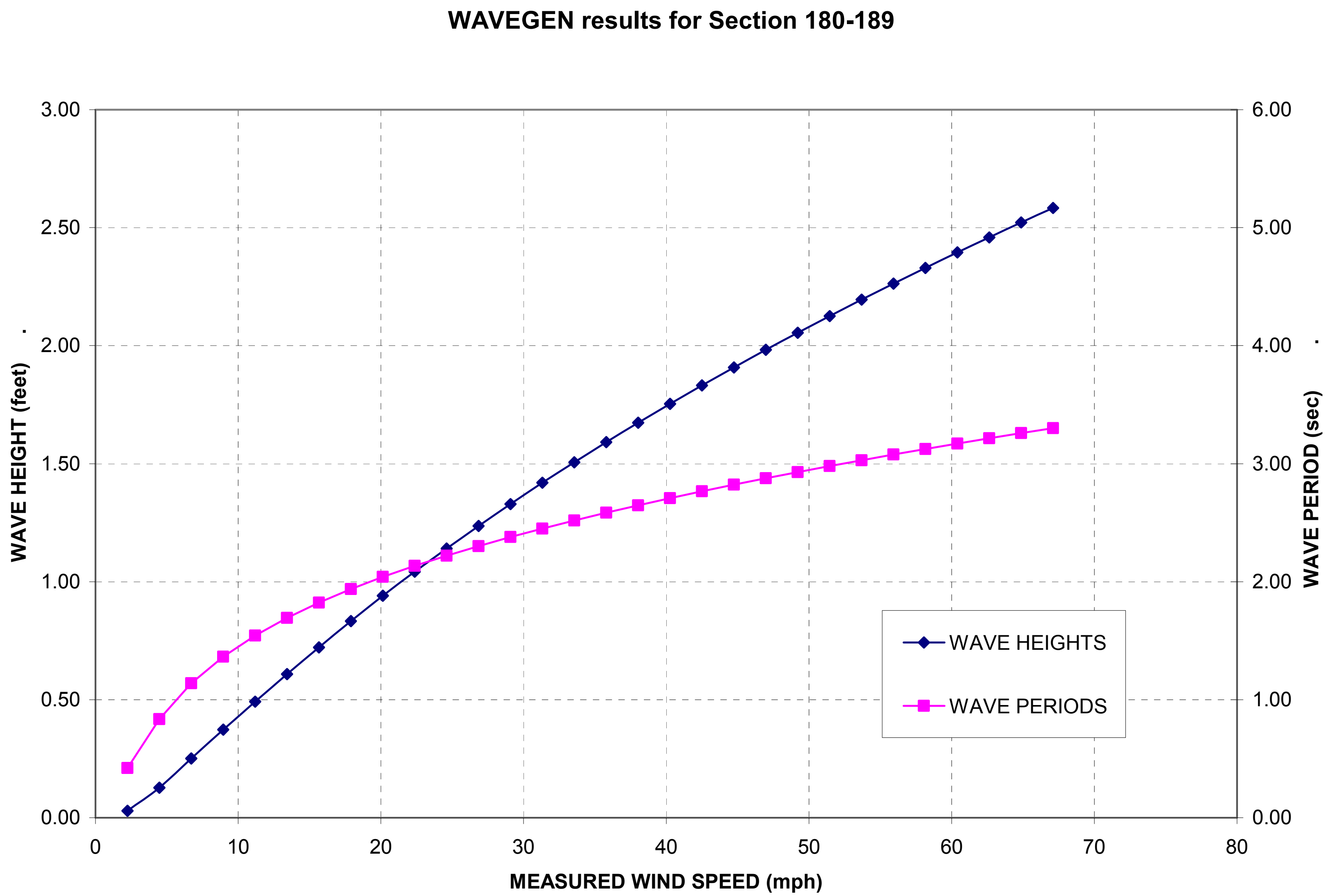


WAVEGEN results for Section 150-159
WAVE HEIGHT (feet)
WAVE PERIOD (sec)
MEASURED WIND SPEED (mph)
WAVE HEIGHTS
WAVE PERIODS
0.00
0.50
1.00
1.50
2.00
2.50
0.00
1.00
2.00
3.00
4.00
5.00
6.00
0
10
20
30
40
50
60
70
80

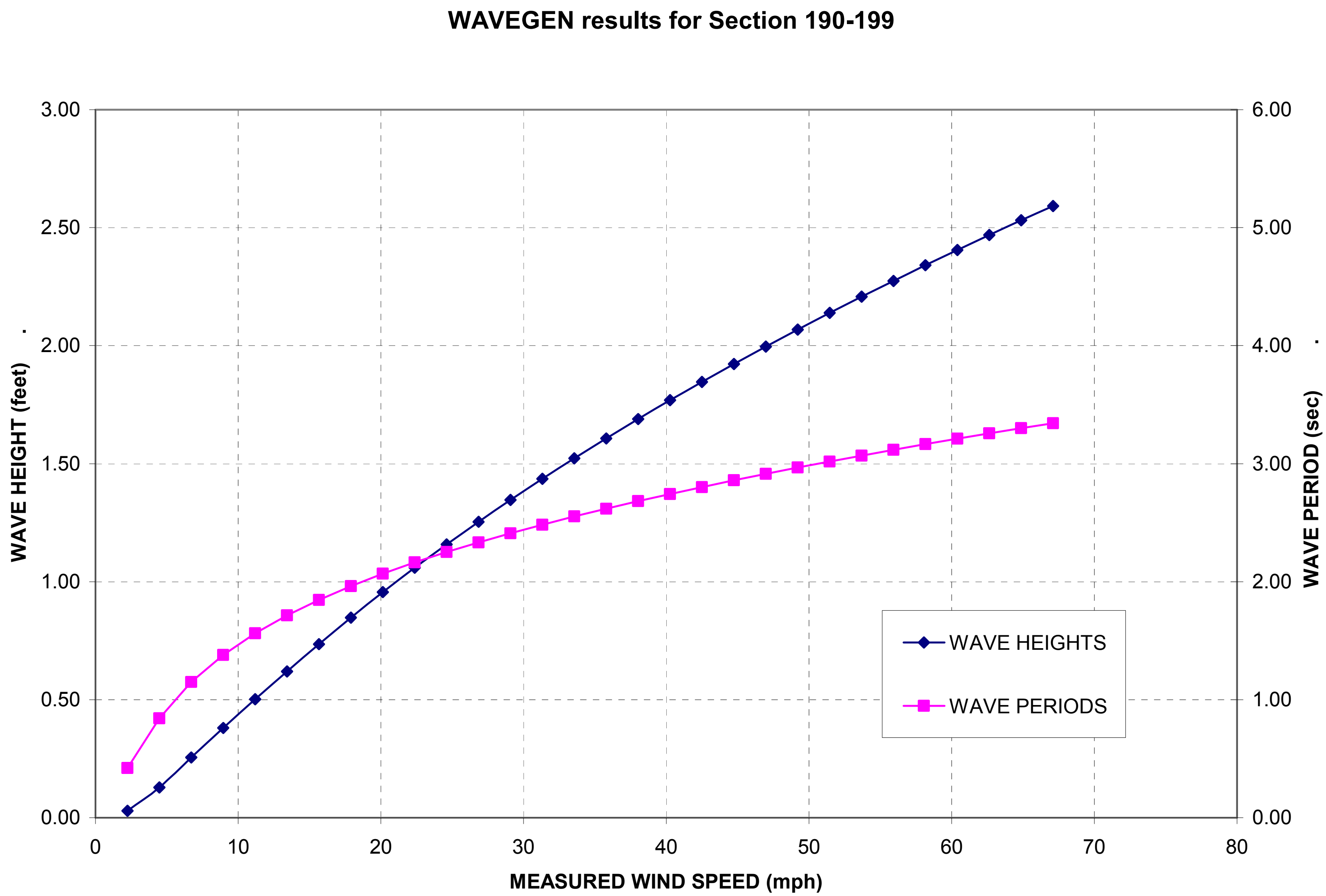

WAVEGEN results for Section 160-169
WAVE HEIGHT (feet)
WAVE PERIOD (sec)
MEASURED WIND SPEED (mph)
WAVE HEIGHTS
WAVE PERIODS
3.00
2.50
2.00
1.50
1.00
0.50
0.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0
10
20
30
40
50
60
70
80

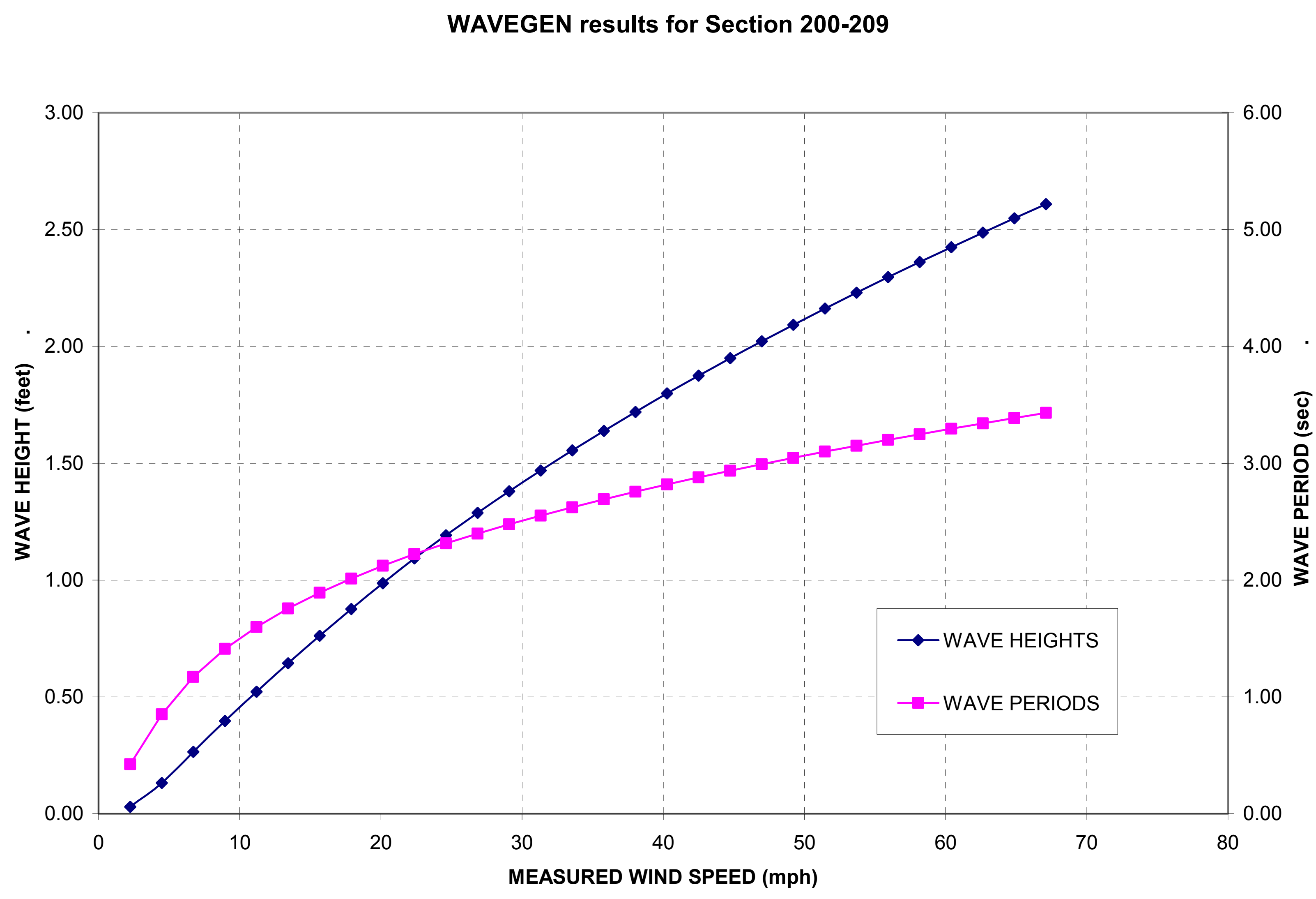


WAVEGEN results for Section 170-179
3.00
2.50
2.00
1.50
1.00
0.50
0.00
WAVE HEIGHT (feet)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
WAVE PERIOD (sec)
0
10
20
30
40
50
60
70
80
MEASURED WIND SPEED (mph)
WAVE HEIGHTS
WAVE PERIODS

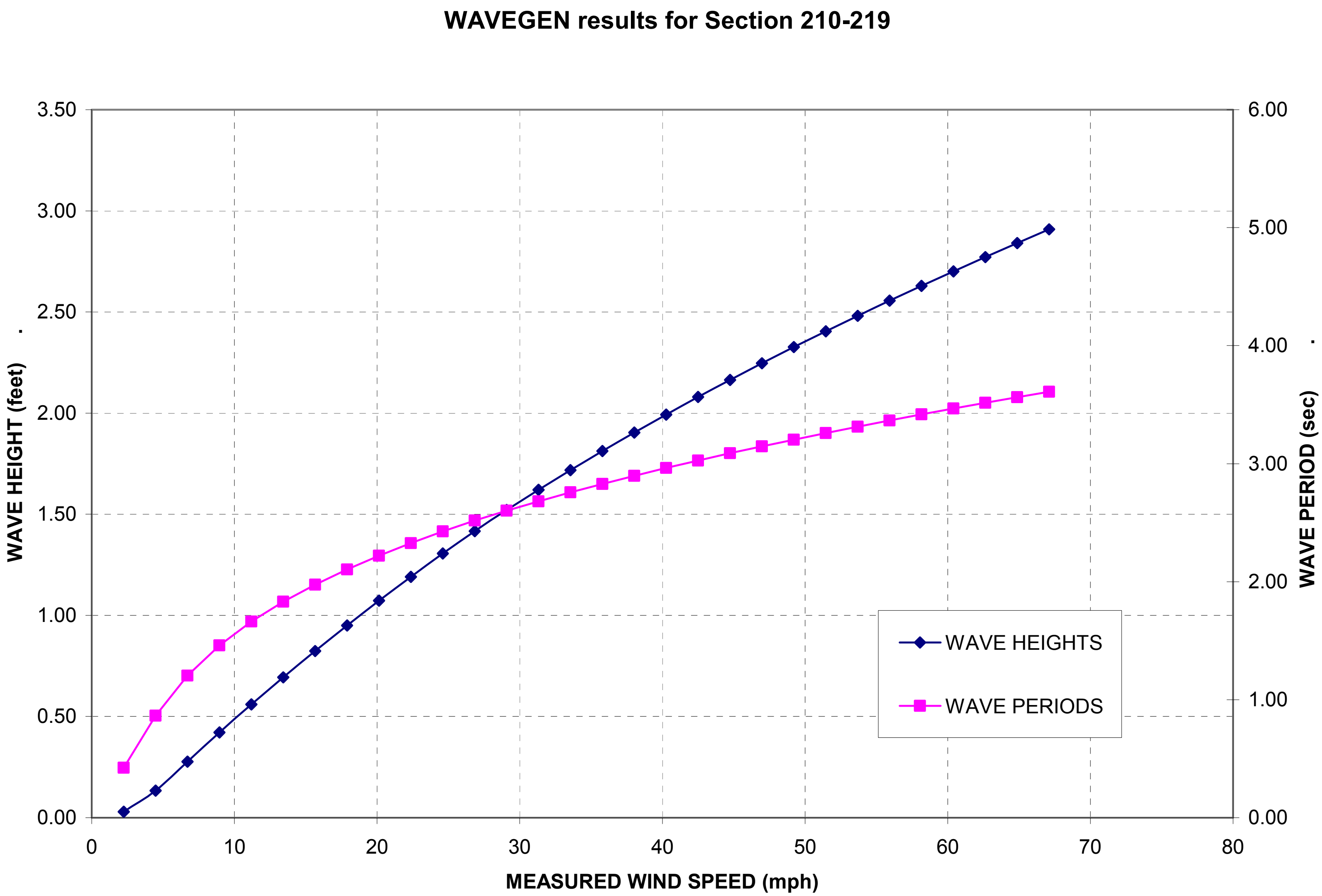


WAVEGEN results for Section 180-189
WAVE HEIGHT (feet)
WAVE PERIOD (sec)
MEASURED WIND SPEED (mph)
3.00
2.50
2.00
1.50
1.00
0.50
0.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0
10
20
30
40
50
60
70
80
WAVE HEIGHTS
WAVE PERIODS

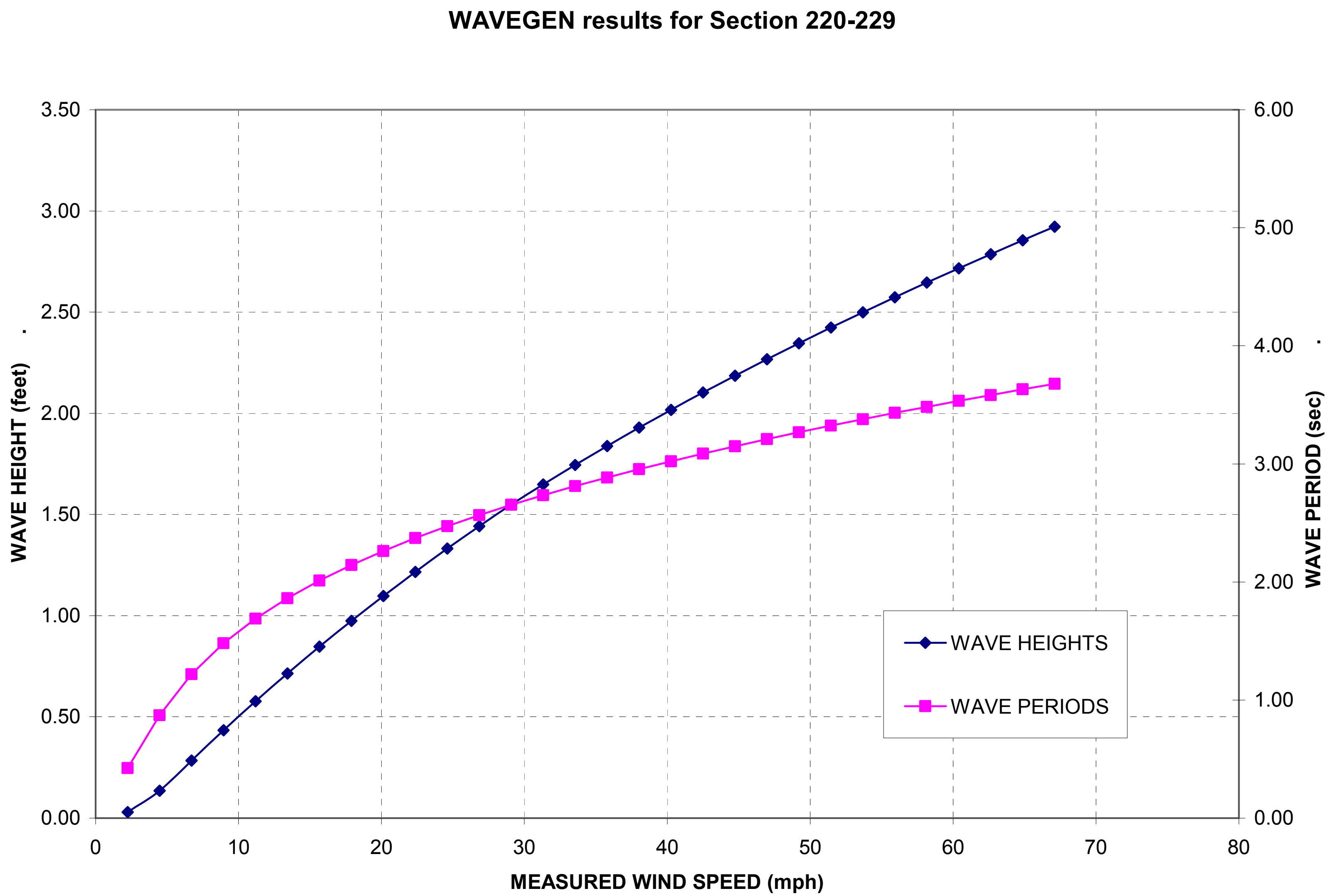

WAVEGEN results for Section 190-199
3.00
2.50
2.00
1.50
1.00
0.50
0.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0
10
20
30
40
50
60
70
80
WAVE HEIGHT (feet)
WAVE PERIOD (sec)
MEASURED WIND SPEED (mph)
WAVE HEIGHTS
WAVE PERIODS



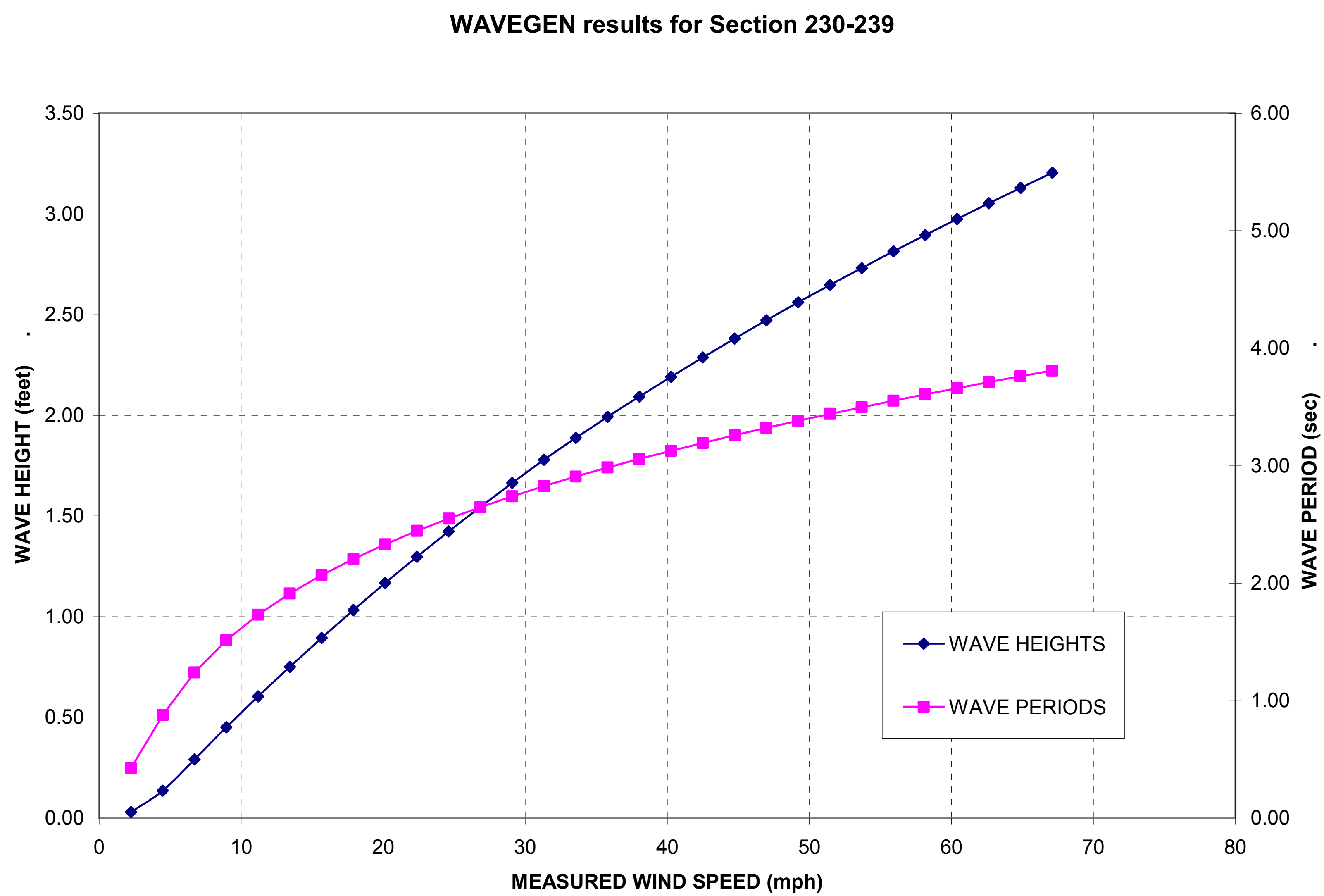
WAVEGEN results for Section 200-209
WAVE HEIGHT (feet)
WAVE PERIOD (sec)
MEASURED WIND SPEED (mph)
0.00
0.50
1.00
1.50
2.00
2.50
3.00
0.00
1.00
2.00
3.00
4.00
5.00
6.00
0
10
20
30
40
50
60
70
80
WAVE HEIGHTS
WAVE PERIODS



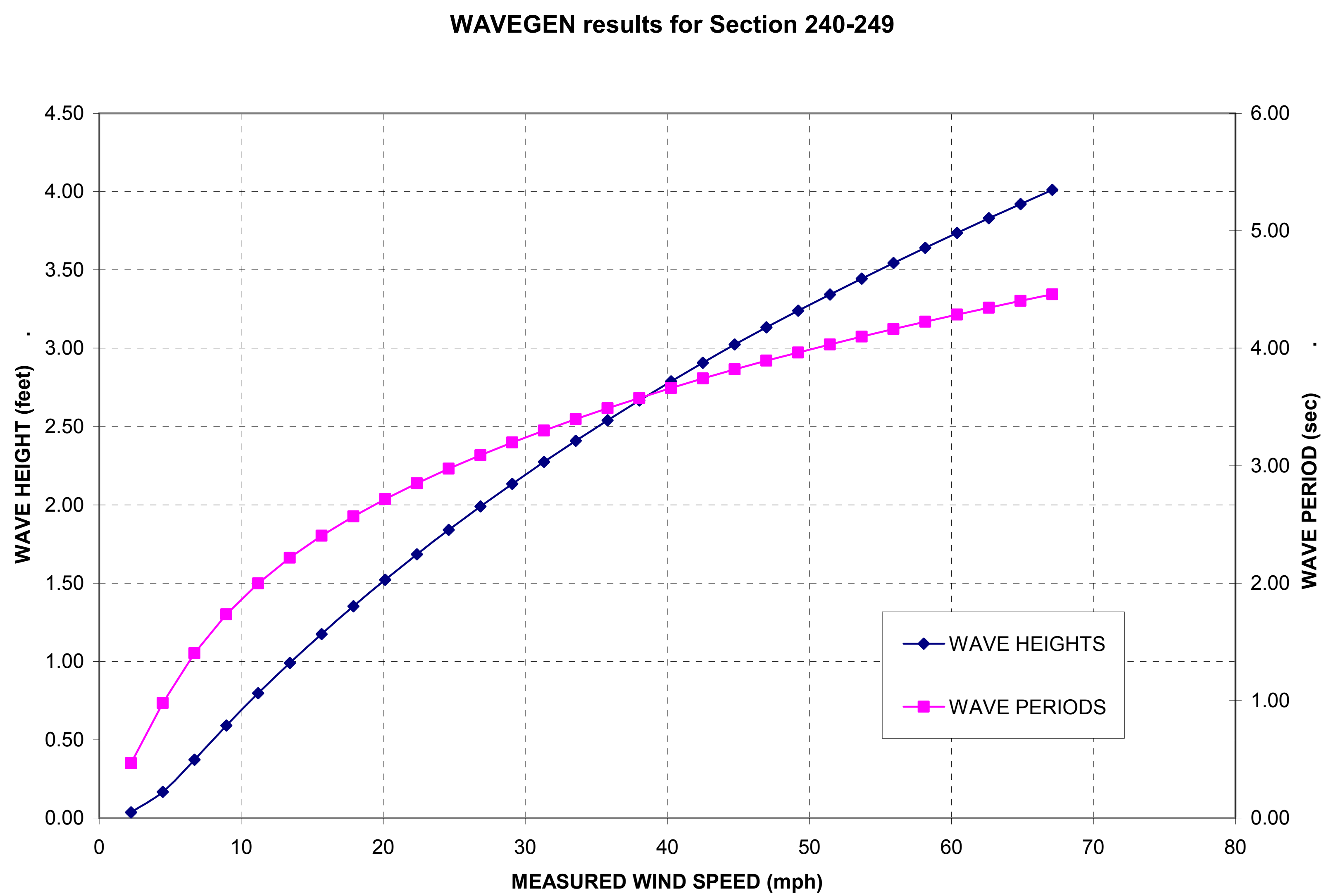
WAVEGEN results for Section 210-219
WAVE HEIGHT (feet)
WAVE PERIOD (sec)
MEASURED WIND SPEED (mph)
WAVE HEIGHTS
WAVE PERIODS
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
1.00
2.00
3.00
4.00
5.00
6.00
0
10
20
30
40
50
60
70
80



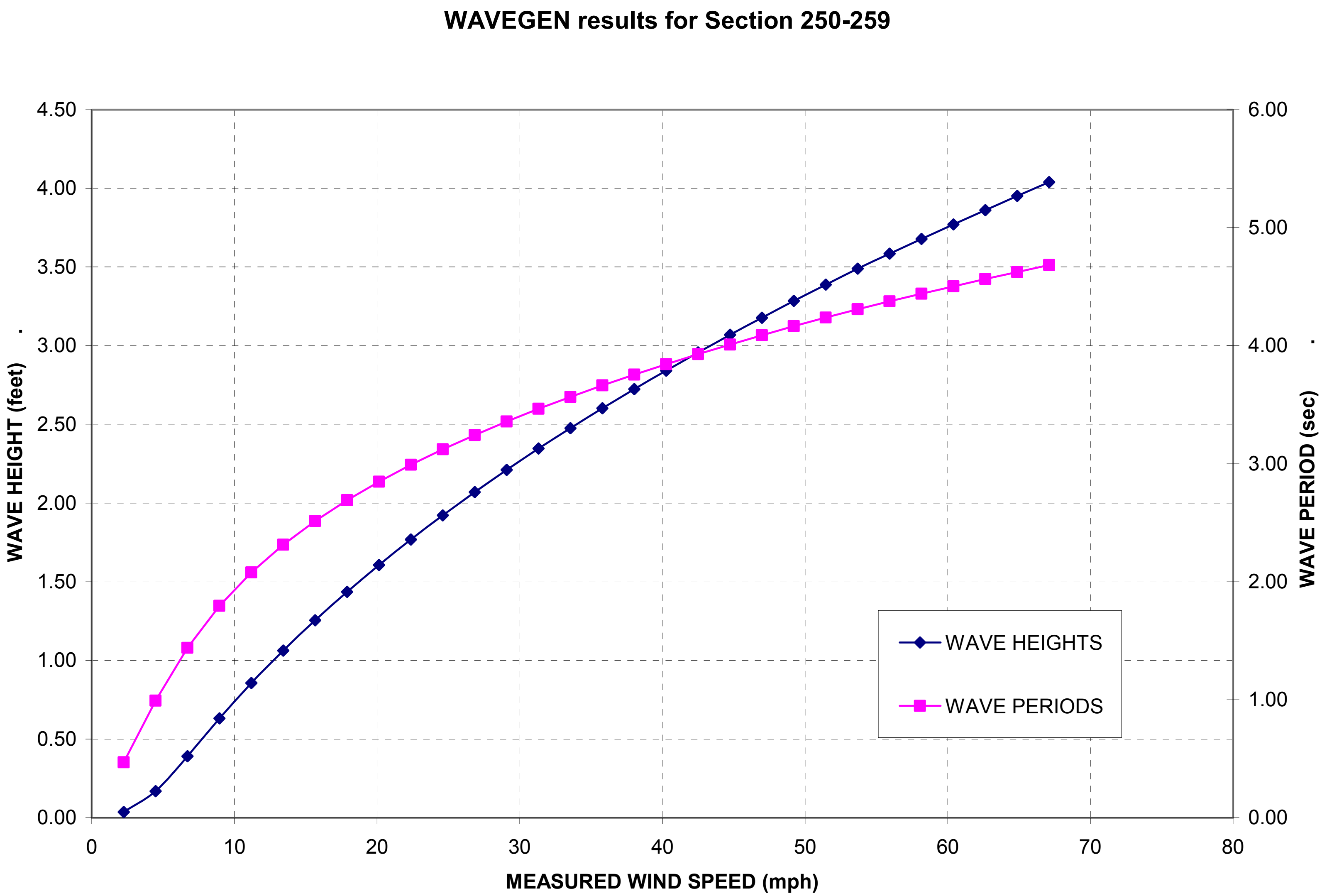
WAVEGEN results for Section 220-229
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
WAVE HEIGHT (feet)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
WAVE PERIOD (sec)
0
10
20
30
40
50
60
70
80
MEASURED WIND SPEED (mph)
WAVE HEIGHTS
WAVE PERIODS



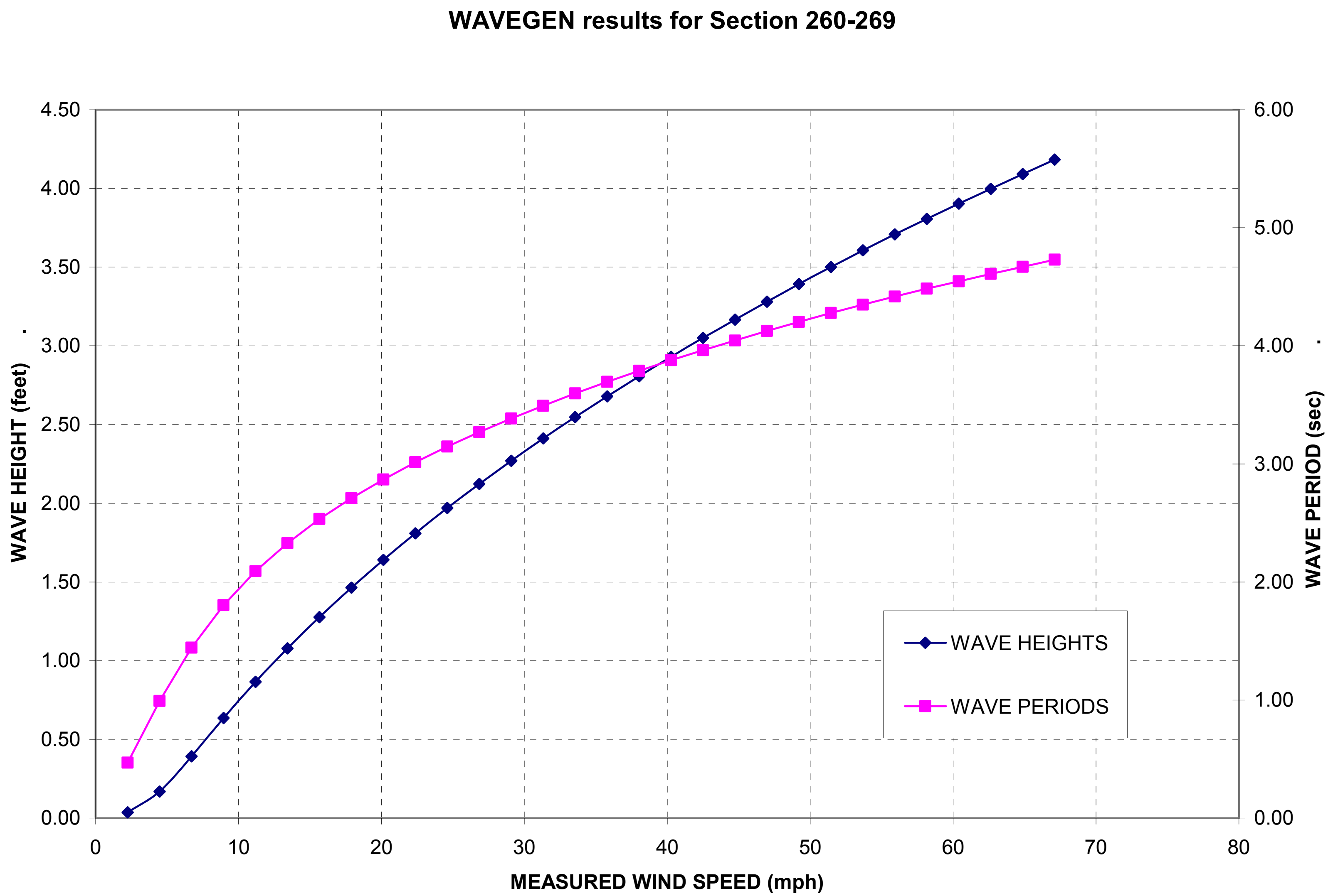
WAVEGEN results for Section 230-239
WAVE HEIGHT (feet)
WAVE PERIOD (sec)
MEASURED WIND SPEED (mph)
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0
10
20
30
40
50
60
70
80
WAVE HEIGHTS
WAVE PERIODS

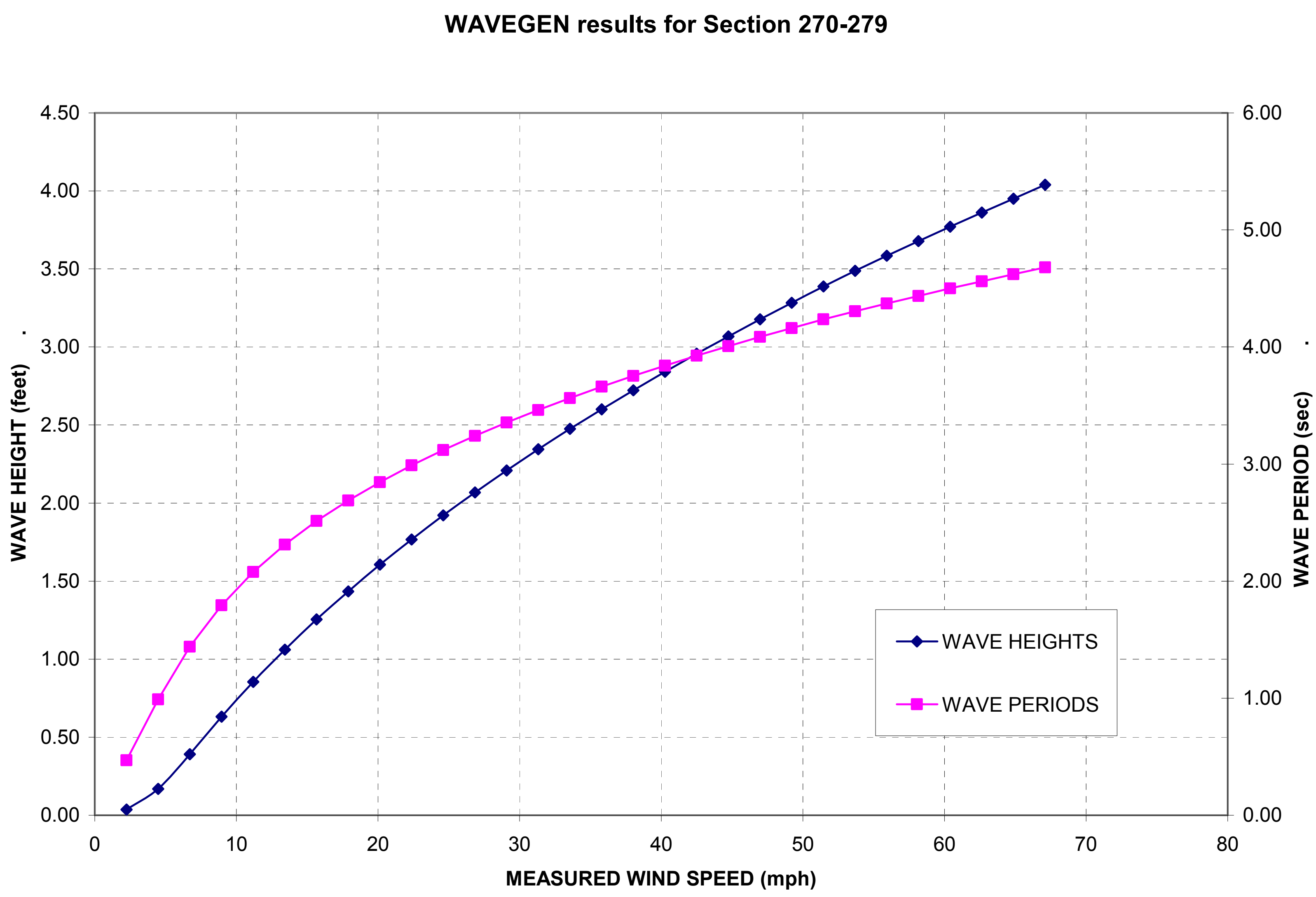


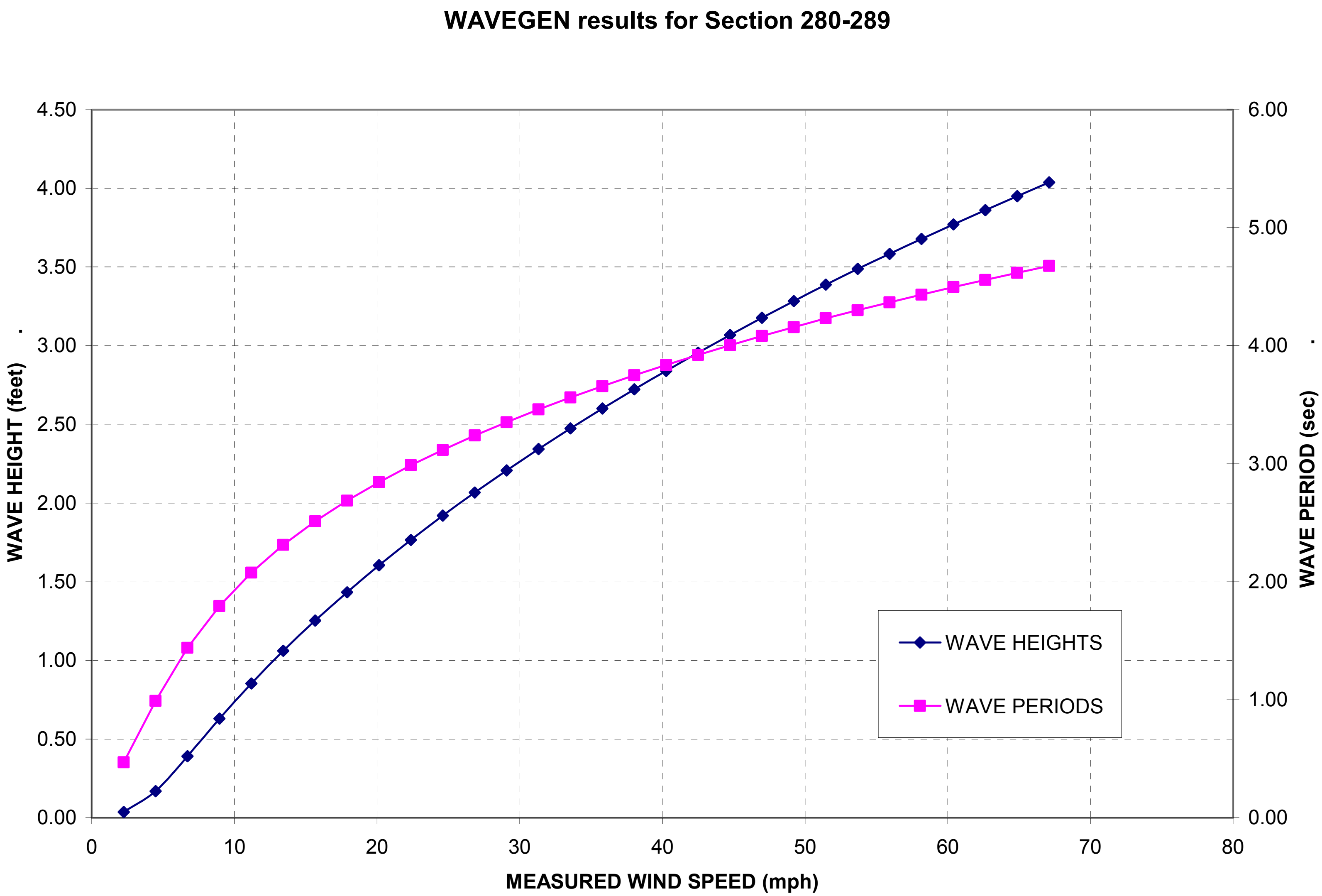
WAVEGEN results for Section 240-249
WAVE HEIGHT (feet)
WAVE PERIOD (sec)
MEASURED WIND SPEED (mph)
WAVE HEIGHTS
WAVE PERIODS
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
0.00
1.00
2.00
3.00
4.00
5.00
6.00
0
10
20
30
40
50
60
70
80

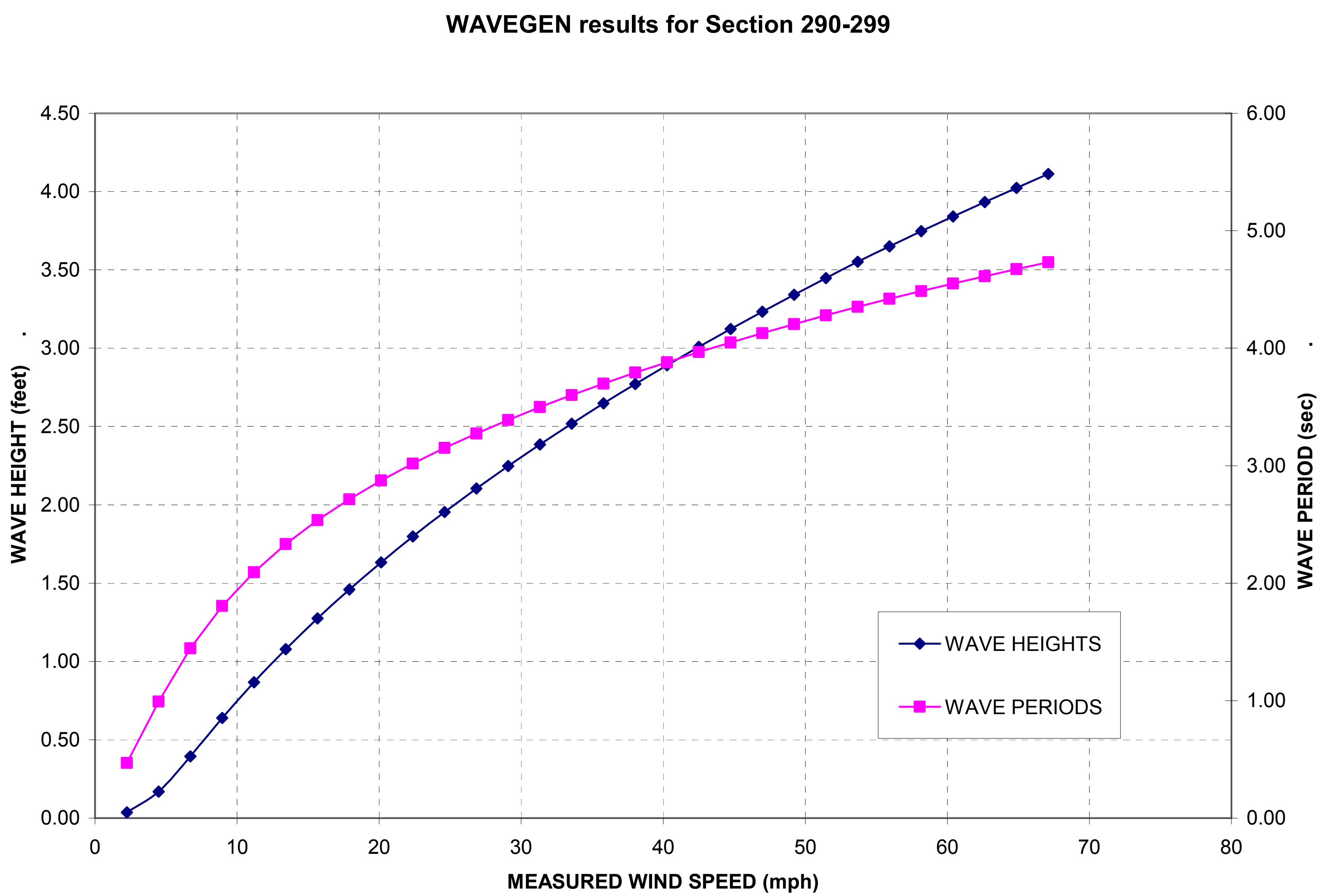


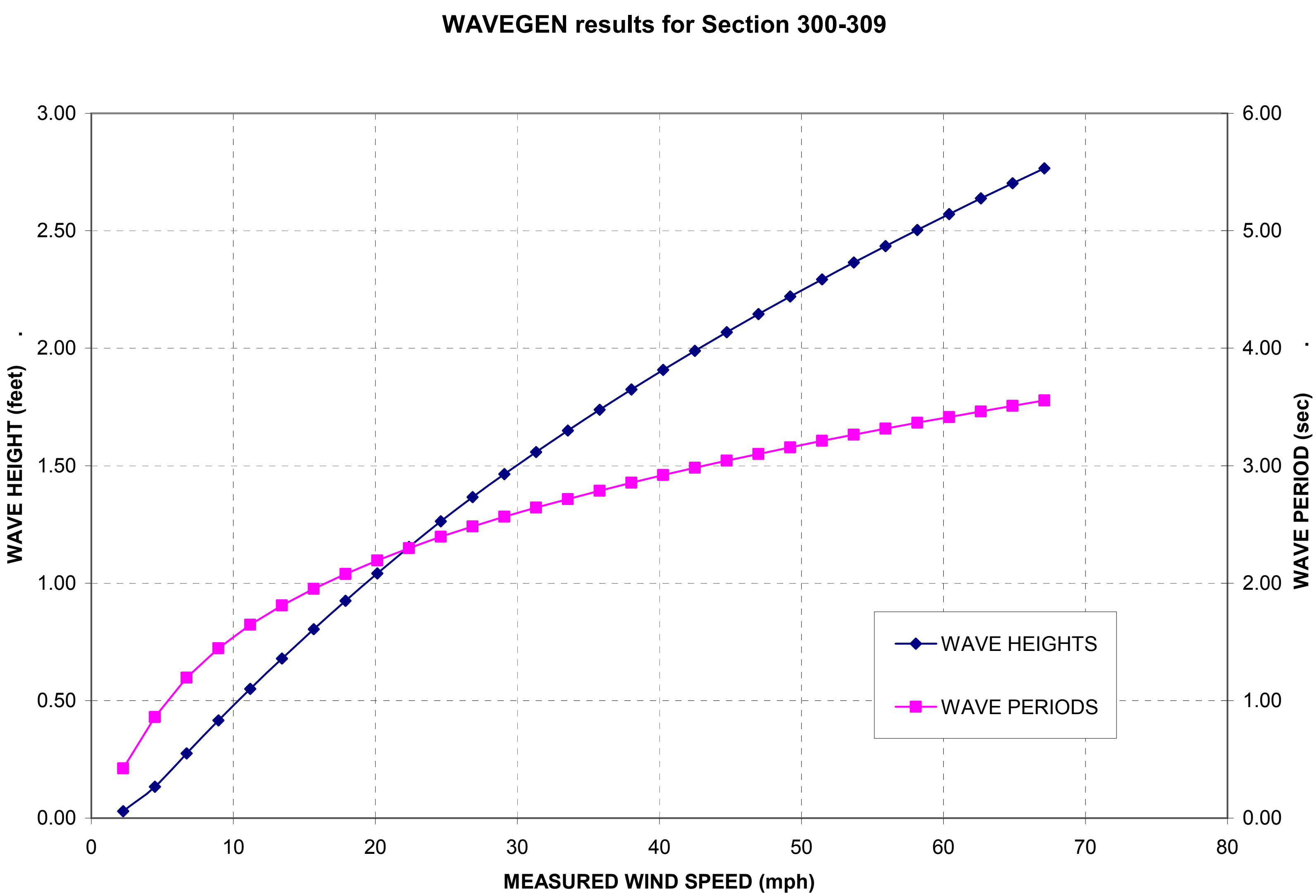
WAVEGEN results for Section 250-259
WAVE HEIGHT (feet)
WAVE PERIOD (sec)
MEASURED WIND SPEED (mph)
WAVE HEIGHTS
WAVE PERIODS
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0
10
20
30
40
50
60
70
80


WAVEGEN results for Section 260-269
WAVE HEIGHT (feet)
WAVE PERIOD (sec)
MEASURED WIND SPEED (mph)
WAVE HEIGHTS
WAVE PERIODS
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0
10
20
30
40
50
60
70
80


WAVEGEN results for Section 270-279
WAVE HEIGHT (feet)
WAVE PERIOD (sec)
MEASURED WIND SPEED (mph)
WAVE HEIGHTS
WAVE PERIODS
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
1.00
2.00
3.00
4.00
5.00
6.00
0
10
20
30
40
50
60
70
80


WAVEGEN results for Section 280-289
WAVE HEIGHT (feet)
WAVE PERIOD (sec)
MEASURED WIND SPEED (mph)
WAVE HEIGHTS
WAVE PERIODS
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0
10
20
30
40
50
60
70
80


WAVEGEN results for Section 290-299
WAVE HEIGHT (feet)
WAVE PERIOD (sec)
MEASURED WIND SPEED (mph)
WAVE HEIGHTS
WAVE PERIODS
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
1.00
2.00
3.00
4.00
5.00
6.00
0
10
20
30
40
50
60
70
80



WAVEGEN results for Section 300-309
WAVE HEIGHT (feet)
WAVE PERIOD (sec)
MEASURED WIND SPEED (mph)
WAVE HEIGHTS
WAVE PERIODS
0.00
0.50
1.00
1.50
2.00
2.50
3.00
0.00
1.00
2.00
3.00
4.00
5.00
6.00
0
10
20
30
40
50
60
70
80

APPENDIX E

GRAIN SIZE ANALYIS

E. Grain Size Analysis

Grain Size Analysis
by Jared McKee
6/24/2008

Sample #1

Sieve No.	Sieve Diameter	Cum. Mass	Mass Retained	% Retained	% Passing
8	2.38	0.45	0.45	0.1	99.9
16	1.19	6.47	6.02	1.5	98.4
30	0.595	93.57	87.1	22.1	76.3
50	0.297	373.23	279.66	70.9	5.4
100	0.149	391.35	18.12	4.6	0.8
200	0.074	393.47	2.12	0.5	0.3
<200	0.01	394.54	1.07	0.3	0.0

Sample #2

Sieve No.	Sieve Diameter	Cum. Mass	Mass Retained	% Retained	% Passing
8	2.38	2.2	2.2	0.7	99.3
16	1.19	29.12	26.92	8.1	91.3
30	0.595	159.96	130.84	39.3	51.9
50	0.297	298.69	138.73	41.7	10.2
100	0.149	326.1	27.41	8.2	2.0
200	0.074	331.17	5.07	1.5	0.5
<200	0.01	332.8	1.63	0.5	0.0

Sample #3

Sieve No.	Sieve Diameter	Cum. Mass	Mass Retained	% Retained	% Passing
8	2.38	0.02	0.02	0.0	100.0
16	1.19	0.22	0.2	0.1	99.9
30	0.595	17.93	17.71	5.2	94.8
50	0.297	326.74	308.81	90.0	4.8
100	0.149	342.52	15.78	4.6	0.2
200	0.074	342.75	0.23	0.1	0.1
<200	0.01	343.07	0.32	0.1	0.0

Sample #4

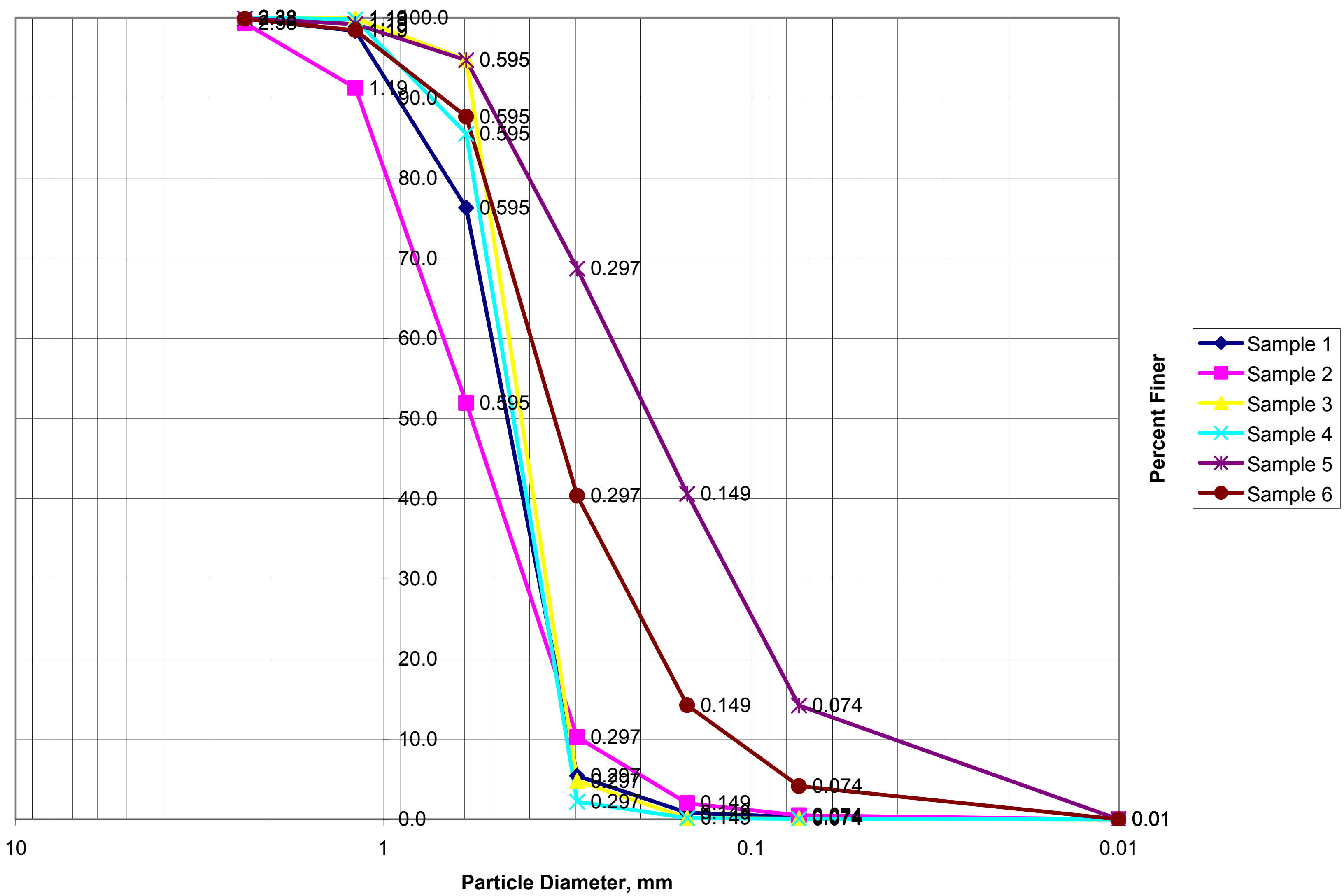
Sieve No.	Sieve Diameter	Cum. Mass	Mass Retained	% Retained	% Passing
8	2.38	0	0	0.0	100.0
16	1.19	0.72	0.72	0.2	99.8
30	0.595	57.24	56.52	14.3	85.5
50	0.297	386.8	329.56	83.3	2.2
100	0.149	394.87	8.07	2.0	0.1
200	0.074	395.26	0.39	0.1	0.0

Sample #5

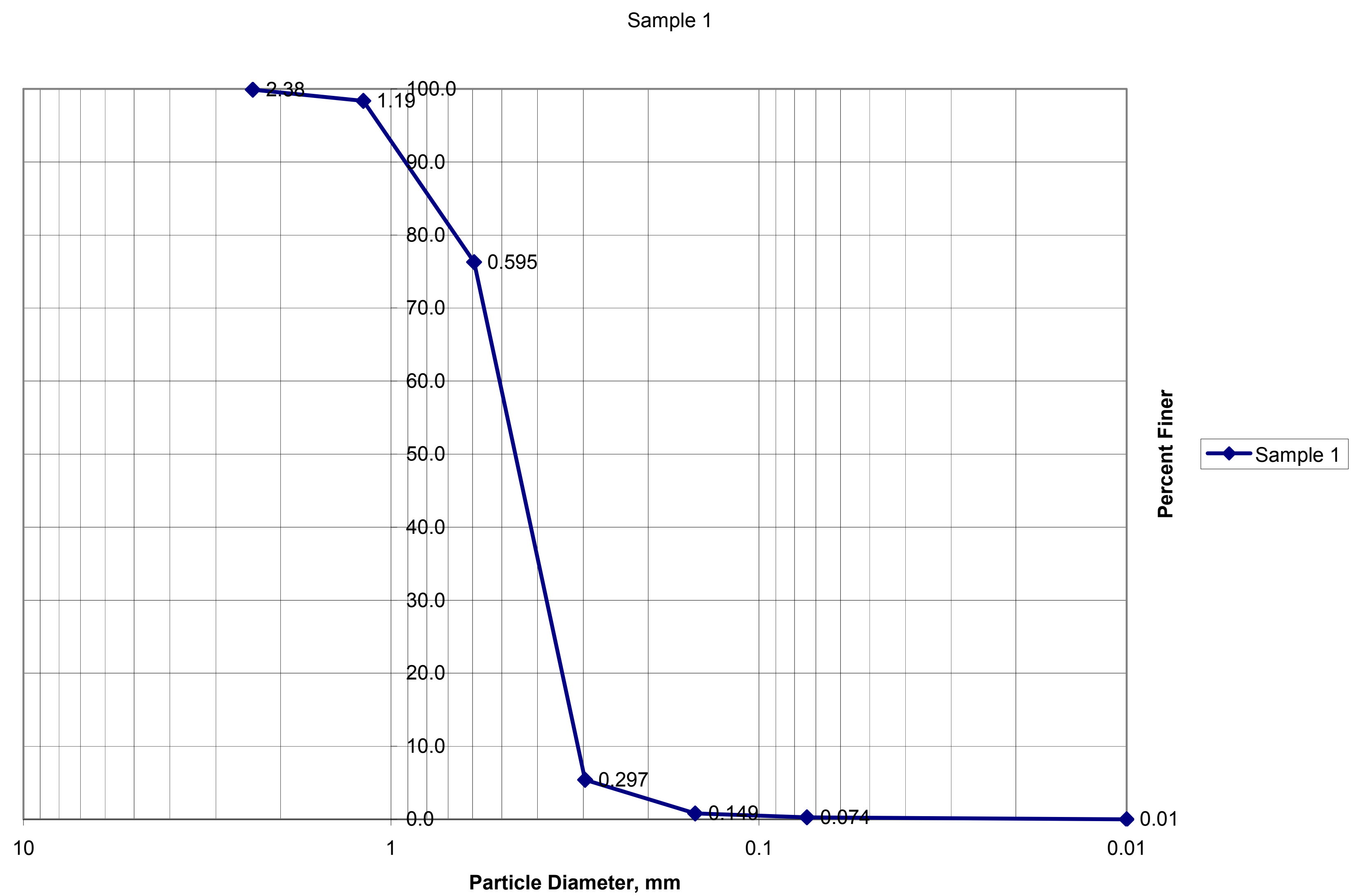
Sieve No.	Sieve Diameter	Cum. Mass	Mass Retained	% Retained	% Passing
8	2.38	0.2	0.2	0.1	99.9
16	1.19	1.51	1.31	0.7	99.2
30	0.595	9.99	8.48	4.5	94.7
50	0.297	59.05	49.06	26.0	68.7
100	0.149	112.16	53.11	28.1	40.6
200	0.074	162.07	49.91	26.4	14.2
<200	0.01	188.86	26.79	14.2	0.0

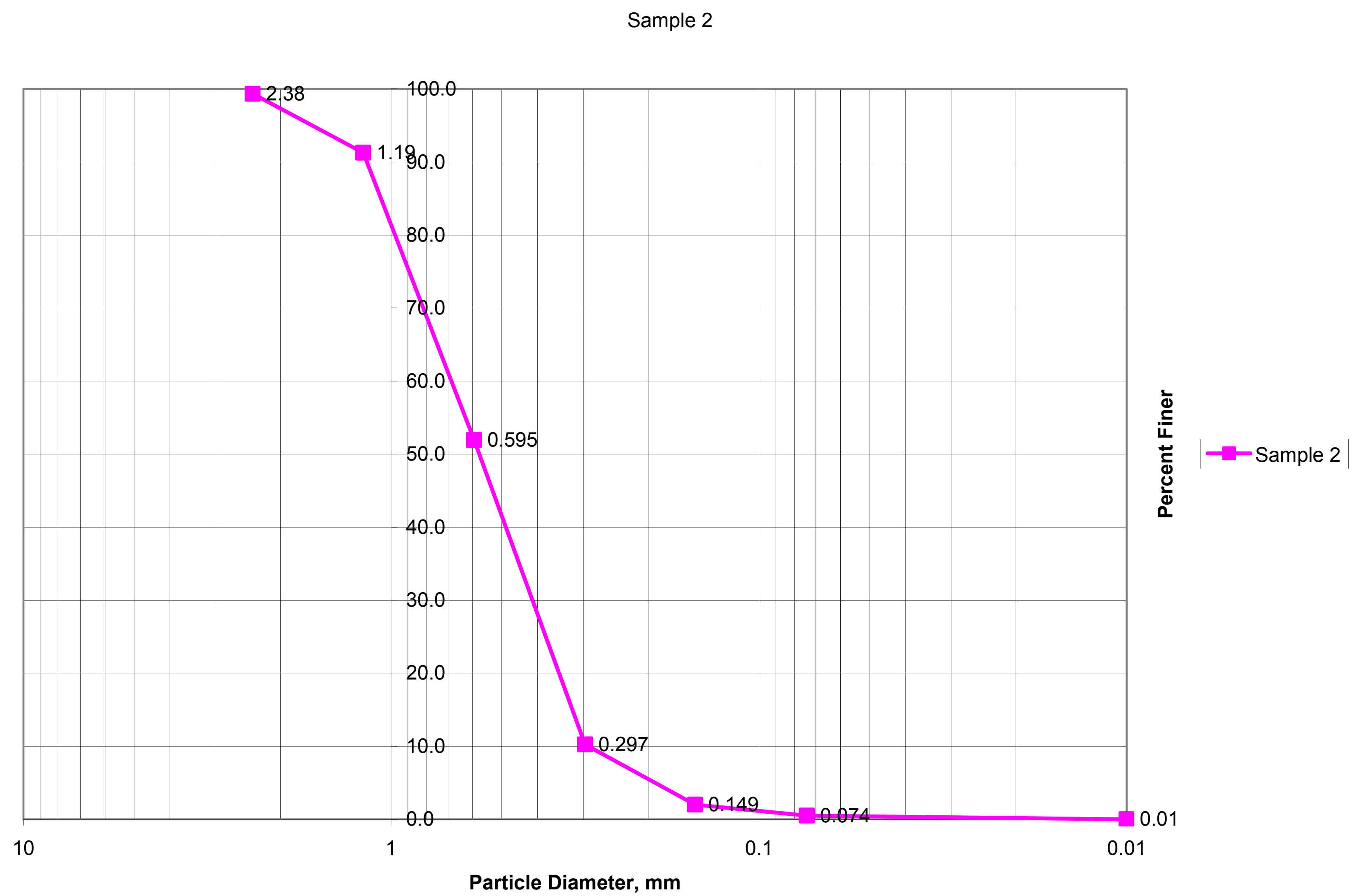
Sample #6

Sieve No.	Sieve Diameter	Cum. Mass	Mass Retained	% Retained	% Passing
8	2.38	0.3	0.3	0.1	99.9
16	1.19	4.28	3.98	1.4	98.4
30	0.595	34.08	29.8	10.8	87.7
50	0.297	164.63	130.55	47.3	40.4
100	0.149	236.76	72.13	26.1	14.2
200	0.074	264.64	27.88	10.1	4.1

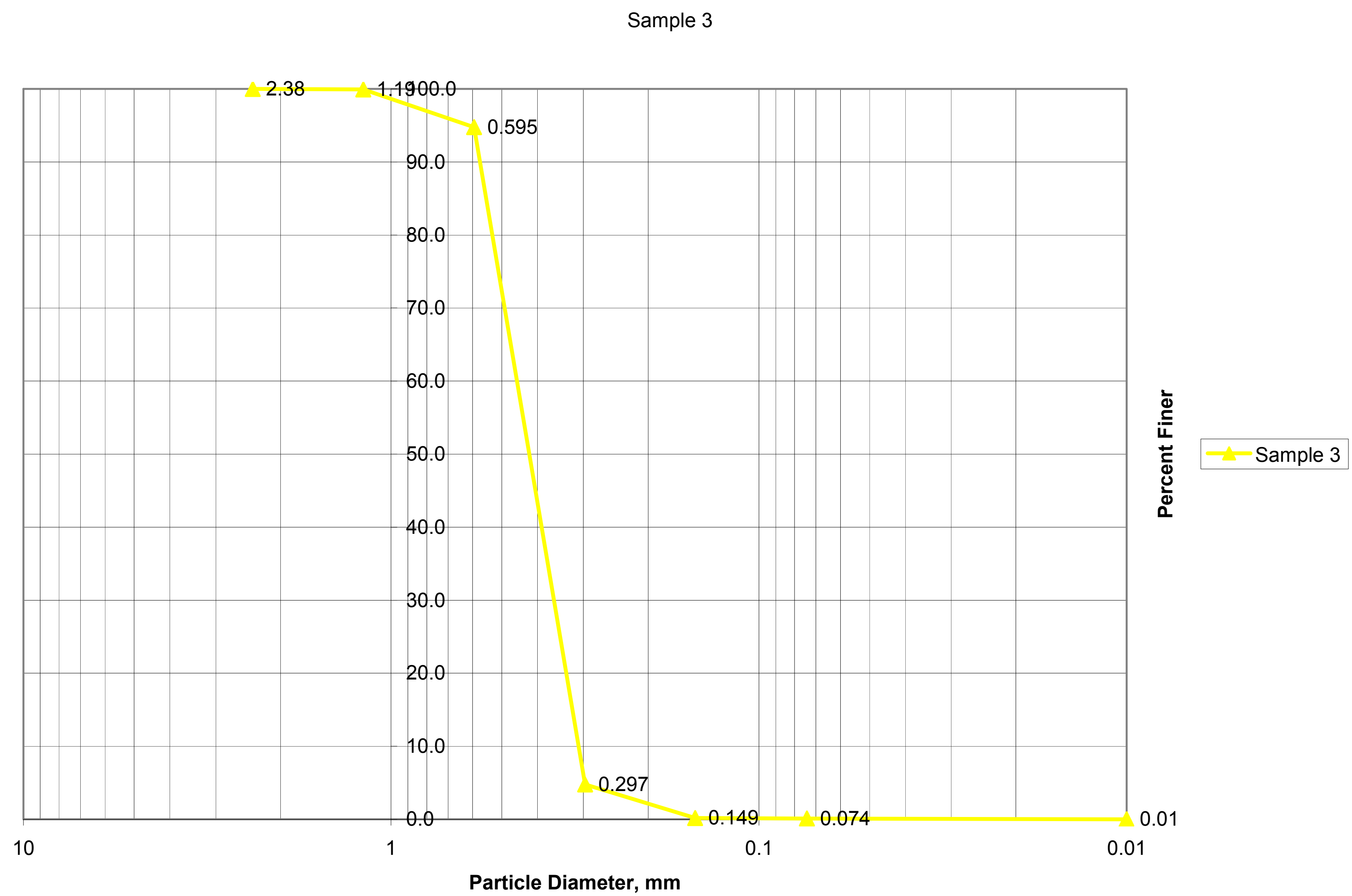


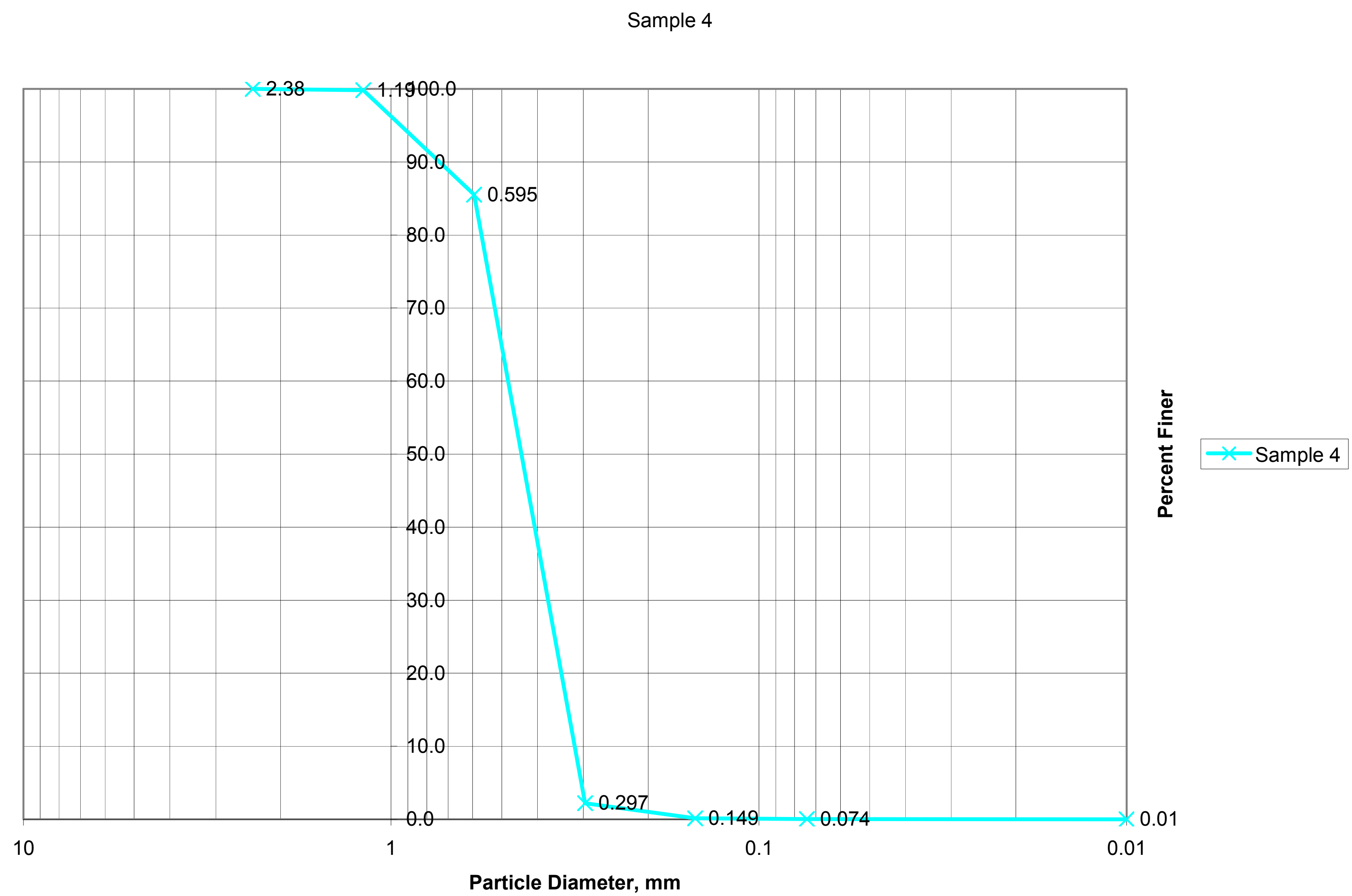
Percent Finer
Particle Diameter, mm
Sample 1
Sample 2
Sample 3
Sample 4
Sample 5
Sample 6
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
10
1
0.1
0.01
2.38
1.19
0.595
0.297
0.149
0.074


Sample 1
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
2.38
1.19
0.595
0.297
0.149
0.074
0.01
10
1
0.1
0.01
Particle Diameter, mm
Percent Finer
Sample 1

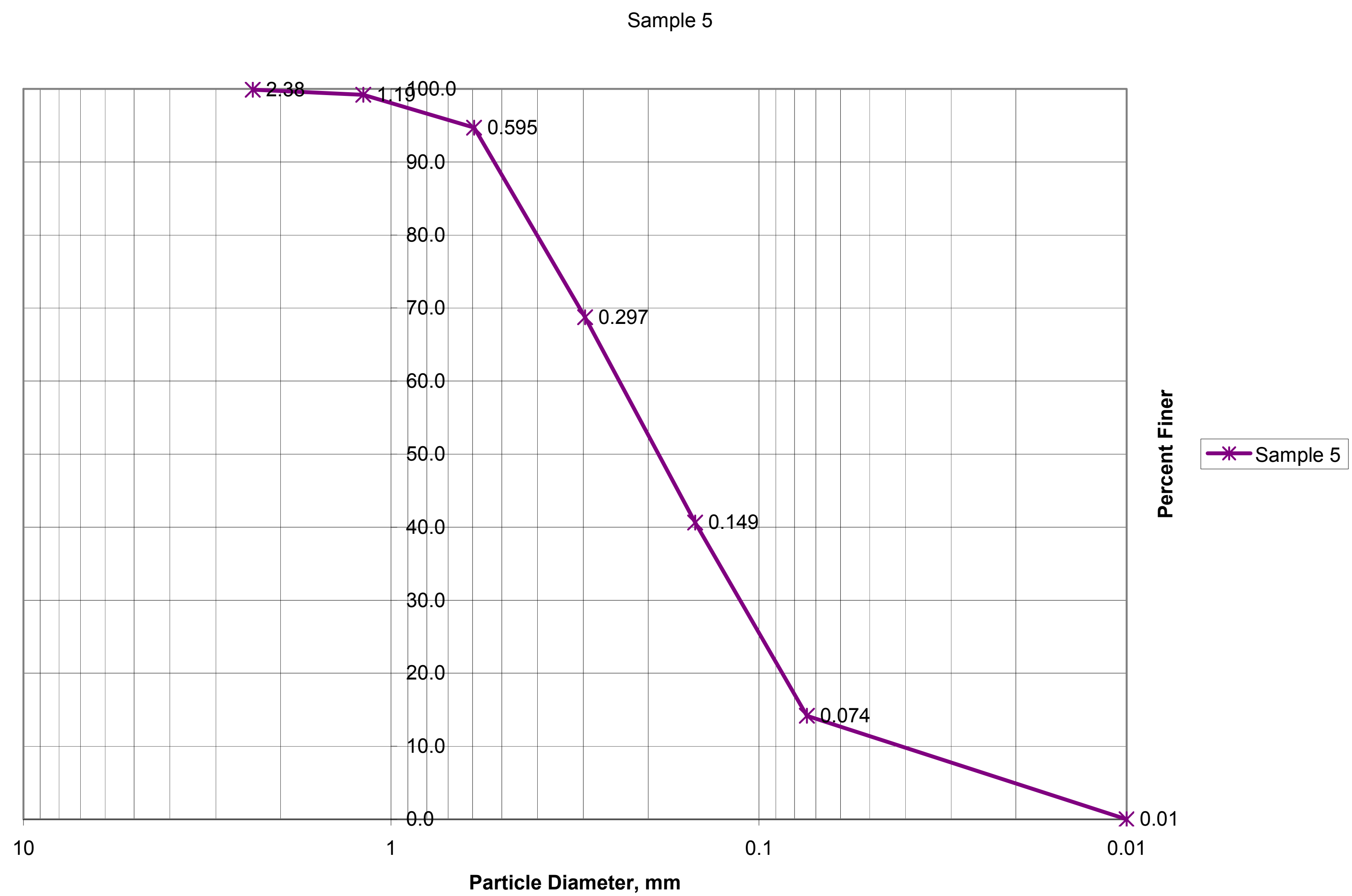


Sample 2
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
2.38
1.19
0.595
0.297
0.149
0.074
0.01
10
1
0.1
0.01
Particle Diameter, mm
Percent Finer
Sample 2


Sample 3
2.38
1.19
100.0
0.595
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.297
0.0
0.149
0.074
0.01
10
1
0.1
0.01
Particle Diameter, mm
Percent Finer
Sample 3

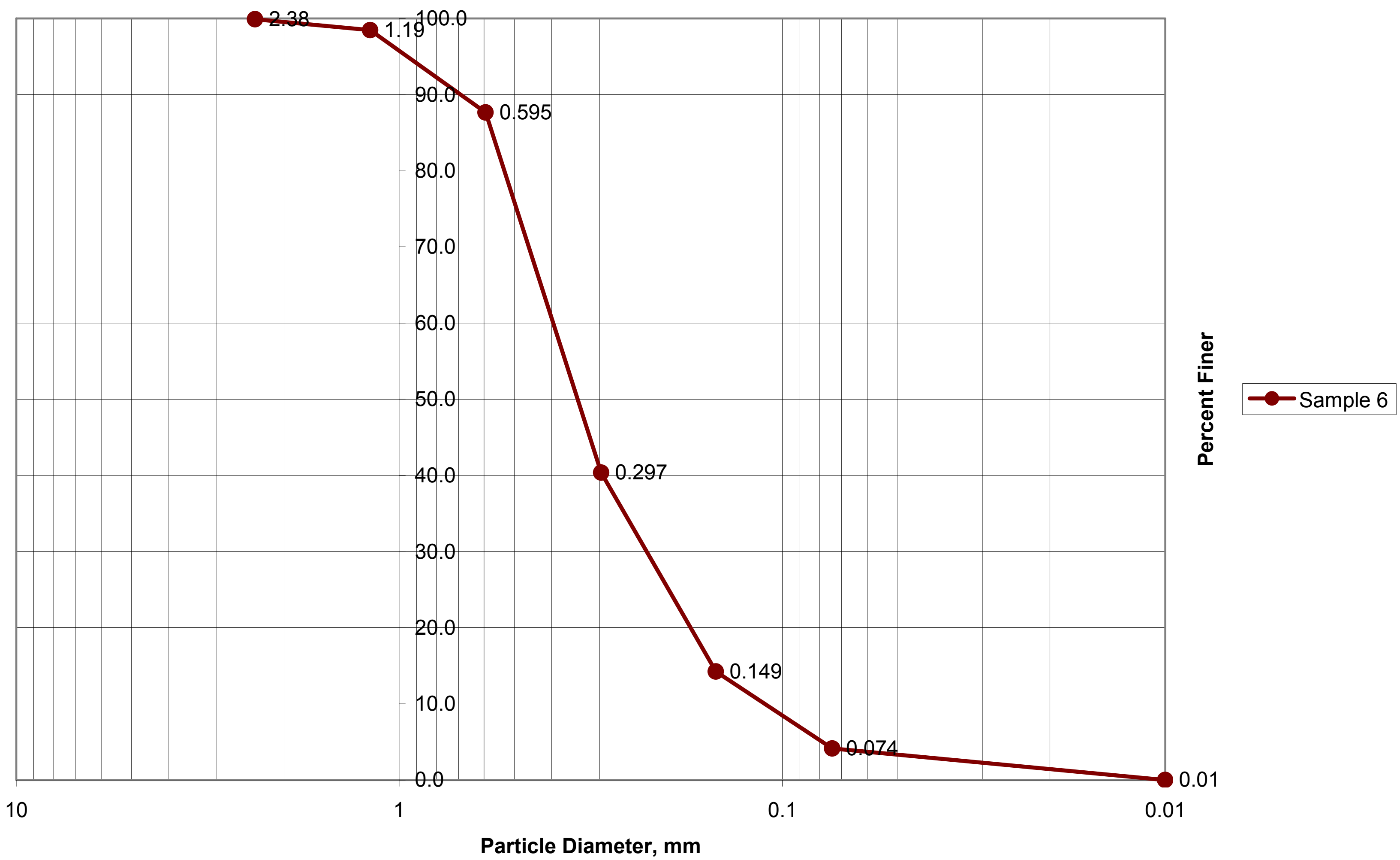


Sample 4
2.38
1.19
100.0
90.0
0.595
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.297
0.0
0.149
0.074
0.01
10
1
0.1
0.01
Particle Diameter, mm
Percent Finer
Sample 4



Sample 5
2.38
1.19
100.0
0.595
90.0
80.0
70.0
0.297
60.0
50.0
40.0
0.149
30.0
20.0
10.0
0.074
0.0
0.01
10
1
0.1
0.01
Particle Diameter, mm
Percent Finer
Sample 5

Sample 6



100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
2.38
1.19
0.595
0.297
0.149
0.074
0.01
10
1
0.1
0.01
Particle Diameter, mm
Percent Finer
Sample 6