

**INFLUENCE OF CONTROLLED DENSITY ARRAYS
OF NATURAL AND ARTIFICIAL VEGETATION
ON FLOW FIELD CHARACTERISTICS**

A Thesis

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LIST OF SYMBOLS

U_z	Mean Horizontal Wind Speed Given at Height z (m)
U_*	Shear Velocity (m/s)
κ	Von Karmann Constant (usual equal to 0.4)
z_o	Height Above the Surface where Fluid Velocity Reaches 0m/s (m)
τ_o	Shear Stress (N/m^2)
ρ	Fluid Density (for this study: 1.15kg/m^3)
τ_s	Shear Stress along the Sediment Surface (N/m^2)
τ_R	Shear Stress along the Roughness Element- <i>Reynolds Stress</i> (N/m^2)
q	Sediment Transport Rate (m^3/s)
U_{*t}	Threshold Shear Velocity (m/s)
A	Empirical Constant (usually assigned a value of 0.1)
σ	Sediment Density (Quartz = 2643 kg/m^3)
C	Grain Sorting Constant (ranges according to degree of sorting)
λ	Roughness Density
L_C	Lateral Cover
S	Total Surface Area Occupied by Roughness Elements
A_S	Frontal Silhouette Area (m^2)
n	Number of Roughness Elements
M	Momentum Flux (N/m^2)
A_C	Area Between Two Velocity Profiles (m^2/s)
A_D	Unit Area Based on the Distance Wind Flow Passes Through Vegetation (m^2)

ABSTRACT

The purpose of this study is to determine the ideal planting density for trapping sediment as a means for determining the most economic and efficient means of foredune development. Research was conducted along the Texas Gulf Coast, within Padre Island National Seashore over a two week period. Four pegboards were aligned perpendicular to oncoming wind direction. Artificial and natural vegetation were plugged into the pegboard at incremental increases in 5% vegetation cover using volumetric measures of both plant types. Both natural and artificial vegetation reduce wind speed proportionately higher between 30% and 50% vegetation density. Natural vegetation has a higher momentum flux compared to the artificial vegetation, however; the rate of change between the two is proportional. This suggests the artificial vegetation may act as a more ideal proxy for natural vegetation rather than solid elements. The sediment flux rate for natural vegetation showed a 90% reduction at a planting density of 18%. This is likely to be the lower limit of vegetation planting for foredune development. The low result in required percent cover for vegetation is likely a function of the low wind speeds experienced throughout the study period and it is suggested that a higher planting density be utilized.

CHAPTER 1: INTRODUCTION

This study is an examination of wind flow through controlled densities of *Panicum amarum* vegetation and artificial plastic vegetation. The aims are to (i) assess how the wind flow behaves through varying plant densities, (ii) examine the relative differences in the flow structure between the two plant types (natural and plastic), (iii) to determine whether artificial vegetation serves as a better proxy for natural vegetation compared to solid elements, and (iv) to estimate the predicted sedimentation rates in varying plant densities. The purpose of this chapter is to introduce the problem context and the purpose of the study.

1.1 Background

It has been estimated that for every one kilometer of barrier shoreline along the Louisiana coast, roughly 30 square kilometers of wetland are protected from damaging wave energy, saltwater intrusion and storm surges (McBride and Byrnes, 1997; van Heerden & DeRouen, 1997). This protection is continually threatened by subsidence and barrier degradation. Within the past 100 years, some of Louisiana's barriers have lost up to 75 percent of their total land area (Stone, *et al.*, 1997). With the highest percentage of wetland loss for all of the United States, with 2500 square kilometers having been eroded since 1956, Louisiana is slowly losing some of its most profitable economic resources (Stone, *et al.*, 1997). The State Fisheries Department, which is responsible for commercial, recreational, and tourist activities in and around wetland regions, account for \$2.5 billion of Louisiana State revenues per year (van Heerden & DeRouen 1997). A considerable decline from such economic revenues will likely arise if the barrier system of Louisiana is not maintained. Threats of decreasing revenues, increased property damage from storm events, and high rebuilding costs all indicate the need for shoreline

protection and foredune redevelopment as well as new management programs (Manohar, 1970).

Shoreline protection is usually conducted by means of “hard” techniques, which include structures such as sea-walls, groins, and detached breakwaters. However, over time it has become increasingly evident that many of these structures actually increase the rate of erosion thus increasing the threat of potential economical, natural and personal loss (Matias, *et al.*, 2004). Beach nourishment became an alternative means of not only protecting against erosion, but also redeveloping coastal regions that had been subject to previous erosional events (Matias, *et al.*, 2004). Although beach nourishment seems to be a better option than many of the hard structure techniques, nourishment projects are not permanent and may be very short lived. Determining the expected life span of nourishment projects and how often the procedure will have to be repeated has become an issue of concern (Dean and Yoo, 1992; Matias, *et al.*, 2004).

Alternatively, coastal restoration methods that trap and collect sediment already found within the coastal sediment budget have become a preferred method of coastal restoration as they utilize natural processes already occurring within the system (Nordstrom, *et al.*, 2002; Conway and Nordstrom, 2003). These techniques usually include the construction of sand fences, planting natural vegetation, or both. These techniques are designed to trap and collect sediment as a means of re-building a ‘natural,’ protective foredune.

1.2 Problem Context

A key problem with management projects that implement natural vegetation is that there are few parameters or guidelines available that identify the number of plants required per unit area to ensure effective sediment accumulation and dune building.

Although several studies have examined the potential for sediment trapping around solid elements (*e.g.* Marshall, 1971; Raupach, *et al.*, 1993; Al-awadhi & Willetts, 1999; Arens, *et al.*, 2001), there have been few attempts to assess this for natural vegetation. The use of solid objects as proxies for natural vegetation means that it is difficult to extrapolate to natural conditions because the roughness elements that have been studied are static, inflexible and solid, and therefore, do not realistically simulate the flexible and porous nature of natural vegetation.

Lack of investigation of natural vegetation in regards to determining an ideal planting density likely arises from difficulties in manipulating certain characteristics, as well as the labour intensive efforts required to keep vegetation fresh throughout the study period. As a compromise, it may be suggested that artificial vegetation be used as a proxy for natural vegetation. Using artificial vegetation to derive parameters such as ideal planting densities would reduce labour intensity and is more likely to yield results in closer proximity to results from natural vegetation. However, in order to use artificial vegetation as a proxy for real vegetation, the nature of the wind flow and its characteristics in artificial vegetation must first be investigated.

1.3 Purpose of Study

The purpose of this study is to 1) examine the behaviour of wind flow in different densities of natural and artificial vegetation, and 2) to attempt to determine optimum plant densities for sand trapping. The problem of predicting sediment trapping by vegetation has been assessed and re-assessed within the literature; however, results often show significant variability. Most often, current studies only act to solidify generalized paradigms rather than promote further exploration and understanding in regards to the natural environment. Artificial vegetation was created for this study as a means of

establishing a ‘middle-ground’ between solid elements and natural vegetation for the purpose of simplification. This said, the research objectives are as follows:

- To compare flow characteristics between artificial plants, and natural vegetation at controlled density intervals.
- To assess and evaluate the momentum flux for controlled densities of roughness elements and related potential for trapping sediment.
- To assess whether artificial vegetation is more appropriate to utilize as a proxy for natural vegetation compared to solid elements.

CHAPTER 2: LITERATURE REVIEW

This chapter examines the basic aeolian processes that occur as an obstacle interacts with oncoming wind flow. First, the benefits and growth patterns of coastal vegetation are outlined, providing the basis for the purpose of modeling with natural vegetation. Second, the larger scale processes and alteration of the boundary-layer flow over and in vegetation and roughness elements are outlined. Second, smaller scale mechanics are described for both solid objects and natural vegetation. Methods utilized by previous studies to determine vegetation density are discussed, as are concerns regarding current models used to describe flow around obstacles.

2.1 Significance of Vegetation Within the Coastal Environment

Coastal environments are inherently harsh for plant growth and development, specifically the region between the high tide line and the backshore. Coastal plants have to cope with a number of different stresses in order to survive, which include, but are not limited to, high temperatures and heat intensity, sand burial and disturbance, saline sand and sea spray, nutrient deficiencies, and flooding due to swash run-up (Hesp, 1991). As a result, many coastal species have developed special adaptations to cope, including the ability to remain stable in environments subject to moving sand (Palmer, 1975). Here we will discuss the versatility and strength of coastal plants that have allowed them to endure these challenging conditions and how these adaptations increase the potential for sediment deposition.

2.1.1 Coastal Vegetation Growth and Adaptations

An example of three major plant species found to dominate the foredune region of the study site include bitter panicum (*Panicum amarum*), sea oats (*Uniola paniculata*), and gulf croton (*Croton punctatus*). Coastal plants such as these generally propagate

through seed germination or by extending rhizomes out from the main plant into surrounding areas where new plants can then develop (Hesp, 1991). Palmer (1975) suggests that this mechanism not only sustains continued plant growth as rhizomes extend upward with the new sediment surface, but also act as additional roughness elements over the sand surface, increasing the potential of the plant to trap and bind sand.

Studies regarding seedling germination and growth patterns among dominant coastal plant varieties indicate a positive feedback relationship to a continuous sediment supply to the back beach region (Maun and Lapierre, 1984; Maun and Lapierre, 1986). Maun and Lapierre (1986) found that in order for several of the coastal plant varieties to germinate, a positive sand supply was required to a certain limit. Burial by sediment was also related to the continuous, healthy development of pioneering grasses (Maun and Lapierre, 1984). Under the conditions of steady sediment supply over a long time period, there was a high correlation with increased rhizome production and plant development (Maun and Lapierre, 1986). This suggests a symbiotic relationship between coastal plant varieties and the foredune structure where additional sediment along the backshore promotes vegetation growth and development, which will then aid foredune development and beach stabilization.

These adaptations give vegetation the upper hand in management strategies over other static methods that have been adopted such as sand fences. Although fences prove to be efficient at trapping sediment, their rigid structure is subject to strong drag and shearing stress thus causing the point of flow reattachment to develop within a relatively short distance from the backside of the obstacle (Raine and Stevenson, 1977; Fang and Wang, 1997). This suggests that the overall area conducive to depositional conditions is reduced and sediment may accrete vertically until the sediment angle of repose is

reached, or sediment has reached the top of the fence and there are no longer any exposed roughness elements to impede oncoming flow unless another fence is installed.

Vegetation naturally accounts for these problems in four different ways. First, it has the natural ability to grow upwards with sediment accumulation through rhizome development as discussed above. This means that the height of the foredune is limited more so by sediment supply and beach profile (*eg.* Sherman and Lyons, 1994; Psuty, 2004) than by the height of the roughness elements.

Secondly, coastal plants have the ability to rapidly re-colonize regions that have been completely overwashed by storm surge (Snyder and Boss, 2002). Natural vegetation is generally self-maintaining. The natural resilience of vegetation to the harsh conditions of the coastal environment gives it the upper hand over more static structures such as sand fences, which need to be replaced at extra cost if they are undermined or removed by a high storm surge event.

Thirdly, pioneering coastal species are predominantly grasses and sedges, like *Uniola paniculata* and *Panicum amarum* for example; which have elongated, flat or slightly folded leaf blades that give each plant a flexible structure (Gould, 1975). Due to the highly flexible form of the plants, they have a tendency to bend in the direction of flow under high wind velocities. The flat blades of grass align themselves to be roughly parallel to the bed which acts to decrease the distance between each plant, thus increasing its density and reducing the exposed surface area to oncoming flow (Gillies *et al.*, 2002; Hesp, 2002). As the grass bends it causes the wind to skim over the top of the canopy and wind speeds below the grass surface nearest to the bed are reduced to a minimum. This acts to protect the sediment surface in two different ways: 1) it reduces acceleration of flow near the sediment surface, thus reducing the potential for sediment entrainment

and 2) it creates a pocket of reduced pressure and velocity below the grass canopy which creates an environment conducive to sediment deposition (Musick & Gillette, 1990; Aylor *et al.*, 1993).

Fourthly, these pioneering grasses are porous in nature. A multitude of studies have been completed, mostly through the examination of sand fences regarding how porosity alters the potential for sediment entrapment (*for example see* Kim and Lee, 2001; Lee, *et al.*, 2002). Porosity is an important factor to consider because it decreases the drag force applied to the roughness element because the wind flow is able to permeate through the obstacle. This in turn extends the separation envelope further downstream creating a larger pocket of reduced flow momentum and therefore increases the total area available for deposition (Raine and Stevenson, 1977; Fang and Wang, 1997; Vigiak, *et al.*, 2003). Although the pressure and velocity differential between the free stream flow and the leeward return cell for a porous element is much smaller in comparison to solid elements, Raine and Stevenson (1977) point out that the mean wind flow reduction developed behind a porous obstacle serves as a better method for wind attenuation for the purpose of dune building. In other words, roughness elements that have a porosity of roughly 50% are more efficient at trapping sediment in comparison to solid elements.

Pioneering plant species have several factors that provide the upper hand in trapping sediment and maintaining a foredune structure. Vegetation planting should be the primary restoration practice because it enables a more sustainable and efficient method for foredune restoration. Although planting is being implemented more readily, the physical application of developing the most efficient planting strategy has yet to be discovered. This can partly be attributed to the lack of research conducted to estimate the ideal planting density for the purpose of dune building and restoration.

2.1.2 Coastal Restoration Using Vegetation Planting

Using native coastal plants as a management tool for reconstructing of maintaining a foredune is ideal for several reasons. Coastal plants have the natural ability to re-colonize regions that have been completely scoured of vegetation (Snyder and Boss, 2002), although in some instances re-growth may be slower based upon incipient conditions (Courtemanche, *et al.*, 1999). Coastal vegetation is highly adaptive to the local environment and as long as the desired density is reached, the spatial arrangement is insignificant in regards to growth potential (Feagin and Wu, 2005). Also, implementing a management regimen that is based upon natural dune grass species reduces the problems developed by a static fencing system. Adopting flexible planning measures reduces the need for control structures to protect human development (Nordstrom and Lotstein, 1989)

Foredunes act as a barrier between erosive wind and wave action generated by storm events, and highly valued commercial and residential development along the coastal regions (Matias, *et al.*, 2004; Conway & Nordstrom, 2003; Nordstrom, *et al.*, 2002). An experiment conducted along the Texas coast found that dunes that had undergone vegetation planting developed faster than dunes that had no planting (Dahl, *et al.*, 1983). These dunes were also wider than the dunes that had no vegetation planting and were thus able to better withstand the intense wind and wave activity that occurred throughout the study (Dahl, *et al.*, 1983). Specific tests regarding the trapping potential of *Panicum amarum* along the coast of North Carolina suggests sand trapping fences begin accumulating sediment very rapidly after installment compared to newly planted vegetation (Seneca, *et al.*, 1976). However, the same study shows that after an initial growth period, sediment trapped by vegetation exceeds the rate of deposition behind sand fences (Seneca, *et al.*, 1976). This indicates that although installing sand fences do offer

a quick response of sediment deposition, over the long term, vegetation serves to be a more effective and efficient means of sediment deposition.

A study conducted along a Louisiana coastline offered different results (Mendelssohn, *et al.*, 1991). The study was designed to test the efficiency of different sand fence layouts as well as a combination of vegetation planting with sand fencing. It was found that these methods were able to collect up to 1266 cubic meters of sediment and establish a foredune feature roughly six meters in height over a three-year period (Mendelssohn, *et al.*, 1991). However, this study concludes that the vegetation planting was far less efficient at trapping sediment compared to sand fence installations (Mendelssohn, *et al.*, 1991).

Variation between the three studies examined here may be a result of several factors. Both the Texas coast and South Carolina region have a positive sediment budget (Dahl, *et al.*, 1983; Seneca, *et al.*, 1976), whereas the Louisiana coast, specifically Timbalier Island, has a very low sediment supply (Mendelssohn, *et al.*, 1991). This suggests that the effectiveness of sediment trapping by vegetation may be directly related to the available amount of sediment supply so that if there is less sediment supply, there is a decrease in potential for vegetation to grow and collect sediment.

Discrepancies regarding the effectiveness of trapping sediment in vegetation also likely arise from variation in planting densities and plant maturity between each of the studies. The study that took along the Louisiana coast used 13 200 plants, each spaced 0.46 meters apart, over a total area of 2318 square meters, which is a very small percentage of lateral cover (Mendelssohn, *et al.*, 1991). The other research projects used similar spacing however, one example emphasized each planting row was staggered to

ensure maximum coverage (Seneca, *et al.*, 1976), and the other used vegetation that had matured prior to the study (Dahl, *et al.*, 1983).

2.2 Roughness Elements in Fluid Flow

Many studies have been conducted regarding aeolian mechanics and how fluid flow interacts with vegetation, and roughness elements or obstacles in the flow (*see for example* Sullivan & Greeley, 1993; Wolfe & Nickling, 1996; Gillies *et al.*, 2000; Crawley & Nickling, 2003). Analysis of momentum flux, deceleration of flow, and the development of turbulent structures has been widely utilized in applications to windbreaks (Grant & Nickling, 1998; Fryrear *et al.*, 2000, Raupach *et al.*, 2001). These studies provide an important foundation to explore and examine the objectives of this study.

2.2.1 Large-Scale Flow Mechanics

As flow passes over an even, uninterrupted surface, a drag force is imposed tangentially along the bed, which is referred to as shearing stress (Middleton and Southard, 1984). With increasing height above the sediment surface, frictional forces are reduced and velocity will increase until a constant wind speed is maintained. This point occurs where the friction from the surface no longer influences fluid flow. The region of flow acceleration is referred to as the boundary layer and is often represented by a velocity profile as shown in Figure 2.1 where height above the bed is plotted against the y-axis and wind speed is plotted along the x-axis. Boundary layer profiles are theoretically explained by the Law of the Wall, which is a set of equations that describes the stress exerted by the surface on the fluid flow. The Law of the Wall equation is most commonly expressed as:

$$U_z = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right) \quad (1)$$

where U_z is the mean horizontal wind speed at a given height z , u_* is the shear velocity (found empirically from $\tau_o = \rho u_*^2$ where τ_o represents shear stress and ρ is fluid density) and remains constant with increasing height above the surface. κ is the Von Karmann constant and generally assigned a value of 0.40. z_0 , or roughness length, is the height above the bed where velocity reaches zero.

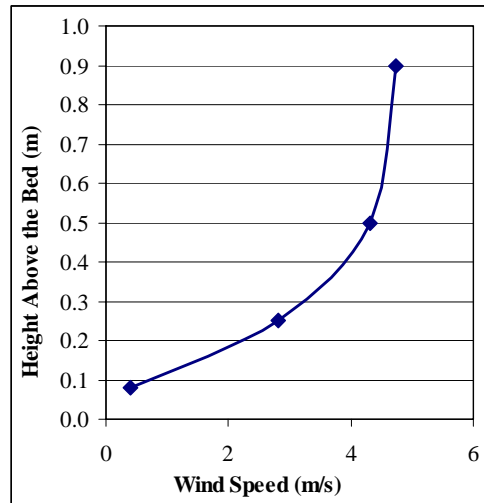


Figure 2.1: Basic velocity profile.

As an object interrupts oncoming horizontal flow, the boundary layer bends causing an upward shift in z_0 , indicating that the obstacle is extracting momentum from the flow around it (Wolfe and Nickling, 1996). Figure 2.2 illustrates this trend more clearly. When an obstacle interferes with oncoming flow it alters the shear stress along the surface and splits it into two components, the shear forces along the sediment surface (τ_s) and the shear stress along the roughness element (τ_R) (Schlichting, 1936; Crawley and Nickling, 2003). This separation of shear stresses is referred to as drag partitioning, and is expressed as:

$$\tau = \rho u_*^2 = \tau_R + \tau_S \quad (2)$$

Increasing the total number of roughness elements for a given area will result in an increase in total drag and shear stress acting upon the roughness elements and a decrease in the shearing stress acting upon the surface (Crawley and Nickling, 2003). Original work conducted by Morris (1955) illustrates three different types of wake flow development, which are later described by Weiriga (1981) and Wolfe and Nickling (1996). Figure 2.3 illustrates the transition of flow with increasing roughness elements. Isolated-roughness flow occurs when the spacing of the objects within an area is great enough that the wake formation behind each obstacle is fully developed and does not interfere with any of the other objects or their associated wake flow (Figure2.3a). With increasing density and decreased spacing between the elements, the wake behind the obstacles begins to interfere with the wake of neighbouring obstacles to varying extents (Figure2.3b). As more elements are added to the same surface area and the spacing between elements decreases further, the wind begins to ‘see’ the array of elements as one single obstacle and the wake generation of individual inner lying elements is suppressed by surrounding elements (Wolfe and Nickling, 1996). This type of flow is referred to as skimming flow (Figure2.3c).

2.2.2 Small-Scale Flow Mechanics

Addressing the smaller scale mechanics of what occurs as the flow approaches an obstacle may help to explain this extraction of momentum more clearly. When a single object interrupts oncoming wind, the flow is forced to separate around the obstacle both vertically and horizontally (Middleton & Southard, 1984; Hesp, 1981). Vertical and horizontal compression of the flow on the windward side of the obstacle causes an

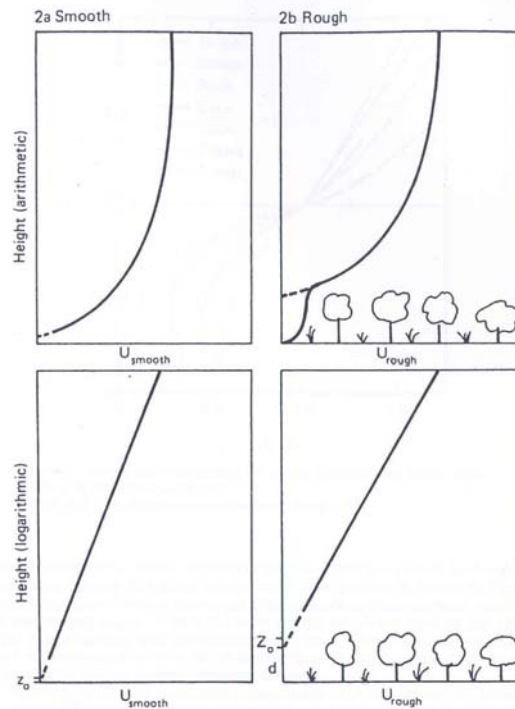


Figure 2.2: Demonstration of profile shifts as roughness elements are introduced. The two upper block show arithmetic velocity profile and how the profile shifts upward when roughness elements intersect the flow. The two bottom images show the same profiles plotted using a logarithmic height to illustrate the shift in z_0 as wind flow encounters an obstacle. From Wolfe and Nickling (1996)

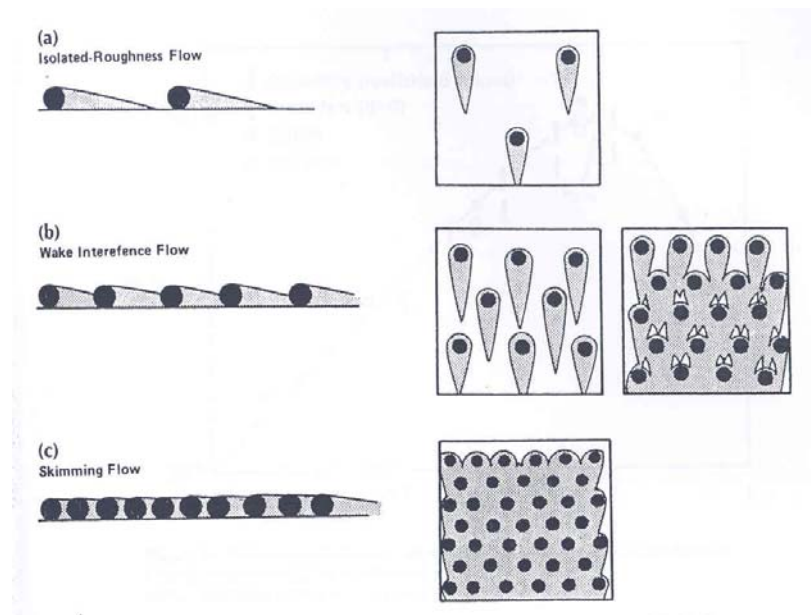


Figure 2.3: Three types flow around various densities of roughness elements. The circles represent the roughness elements and the shaded areas are the wake generated in the lee of these obstacles. From Wolfe and Nickling (1996).

acceleration of flow as it is forced to pass over and around the obstruction. As the wind passes over the object, the flow re-expands and decreases in velocity, creating a pressure differential with a pocket of low pressure developing in the lee of the object (Middleton & Southard, 1984). Commonly referred to as the wake zone or separation envelope, this parcel of air is made up of turbulent flow vortexes called eddies, which become semi-stationary behind the obstacle (Bagnold, 1941; Hesp, 1981). Figure 2.4a demonstrates how flow separates around an obstacle. Raupach (1992) developed a theoretical model that could simplify the wake zone behind a solid cylindrical element into a solid wedge shape as illustrated in Figure 2.4b. From this simplification, Raupach (1992) proposes new methods for quantifying the total stress, the shear stress partition, the roughness length (z_0) and the height of z_0 displacement that develops as skimming flow is reached. Simplifications such as this are often applied in actual field studies to reduce some of the labour intensive calculations or measurements that would be required otherwise. The flow separation envelope of reduced pressure and velocity is responsible for momentum extraction and the upward shift in the boundary layer profile. And, as explained earlier, additional roughness elements increase the potential for momentum extraction, thus inducing a larger momentum flux. Momentum flux may simply be defined as the rate of change in momentum over a unit area (Bagnold, 1941). It is usually recorded by measuring vertical fluxes of horizontal wind vectors and may be visually represented using velocity profiles which illustrate changes in momentum with various heights above the bed for a specified unit length.

A number of various shaped elements have been examined in regards to how they alter surface flow. An early experiment conducted by Schlichting (1936) used a number

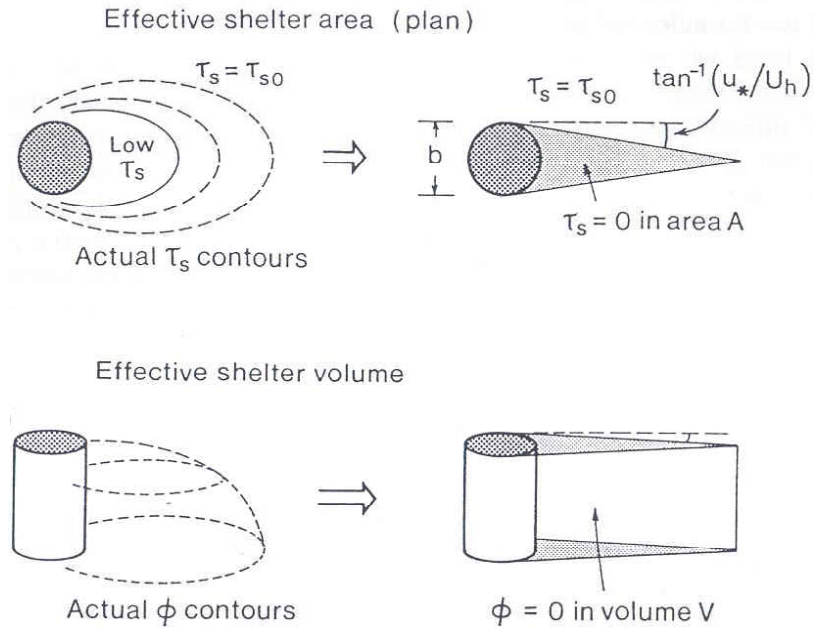


Figure 2.4: Simplification of the shelter zone behind a solid, cylindrical roughness element. The left images are an interpretation of the actual flow separation envelope and the figures on the right demonstrate the simplified representation. From Raupach (1992).

of different shapes acting as roughness elements including spheres, spherical segments, cones, and a flat plates aligned perpendicular to oncoming wind. More recent studies have included cubes (Schlichting, 1936); hemispheres (Marshall, 1971); bushel baskets (Kutzbach, 1961); reed stems (Arens, *et al.*, 2001); and non-erodible cylinders both in the field (Al-awadhi and Willetts, 1999) as well as in a wind tunnel (Marshall, 1971; Sullivan and Greeley, 1993; Crawley and Nickling, 2003). These results have provided an excellent example of how flow separation, shear stress, and drag forces change depending on the size, shape, flexibility and porosity of the obstacle the wind encounters.

2.3 Flow Through Vegetation

Vegetation reacts to oncoming fluid flow very differently in comparison to static and solid elements discussed above. Vegetation is both porous and flexible meaning that

its overall morphology can become altered depending on flow characteristics such as velocity and direction. At lower wind speeds, the leaves of vegetation naturally align themselves so the maximum projection area is perpendicular to oncoming wind flow (Middleton and Southard, 1984). As wind velocities increase, vegetation is more likely to bend with the oncoming flow with the leaves become aligned parallel to wind flow so surface area exposed to oncoming winds is reduced (Gillies, *et al.*, 2002). This inevitably increases the porosity of the plant, reducing friction as the flow passes through the plant (Gillies, *et al.*, 2002).

With the combination of increasing the pore spaces of the vegetation through the alignment of leaves, the swaying and flexing of stems or branches, and the fluttering of leaves, the wake zone that develops in the lee of the vegetation is far more turbulent than those developed by solid elements, which often have a pocket of dead air space. Thus, it may be stated that the wind flow around and through vegetation is considerably different to the flow around solid elements. Figure 2.5 illustrates the flow separation envelope as it develops behind natural vegetation as well the manner in which flow is able to pass through the vegetation as discussed previously.

2.4 Wake Interference and Sediment Deposition

In terms of sediment trapping, eddy development and the reduction of pressure and velocity in the wake of an obstacle creates an environment conducive to sediment deposition (Bagnold, 1941). As the flow decelerates in the wake zone, it loses its potential to transport or carry sediment. As a result, entrained sediment is dropped out of the flow into this region, creating a zone of deposition directly behind the obstacle and forming a shadow dune (Bagnold, 1941; Hesp, 1981). In regions with a higher density of

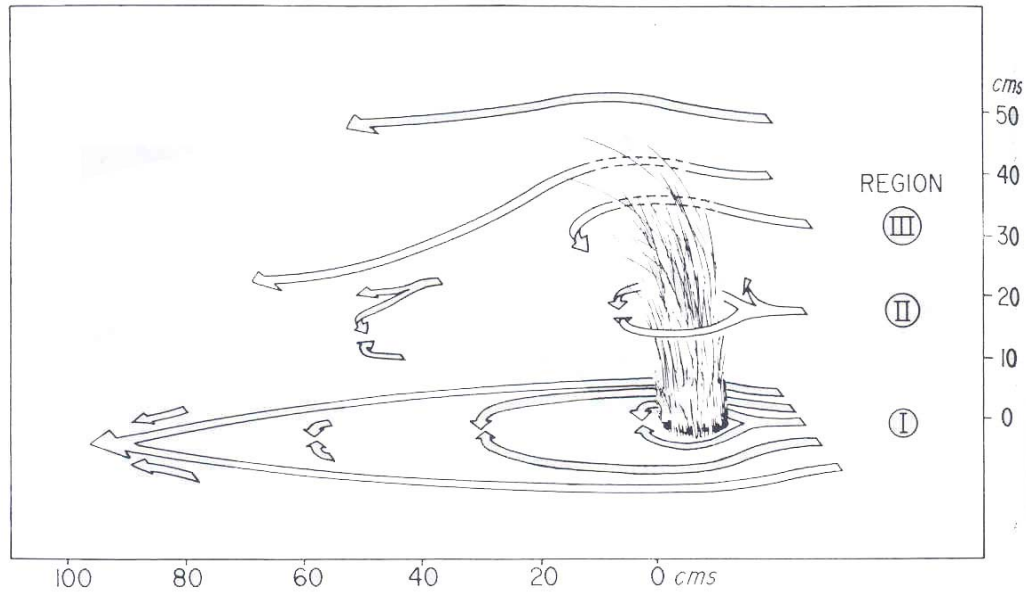


Figure 2.5: Depiction of flow separation envelope behind natural vegetation. Arrows indicate the direction of wind flow (from Hesp, 1981)

roughness elements where skimming flow is maintained, the entire region between the obstacles becomes a zone of deposition because the whole area becomes a low pressure zone with velocities too slow to re-entrain the particles of sediment (Allen, 1985).

Based on these fundamental principles and other variables within the natural environment including surface slope and moisture levels, several studies have been conducted on how sediment may be transported (Belly, 1964; Hotta, *et al.*, 1984). The parameters that influence the sediment transport rate (q) are outlined by Sherman and Lyons (1994) as:

$$q = f(d, \sigma_d, u_*, \sigma_{u_*}, \rho, \rho_s, g, \alpha, w) \quad (3)$$

where σ_d represents the standard deviation of sediment size, σ_{u_*} is the standard deviation of shear velocity, ρ_s is the sediment density, α represents the surface slope, and w is the gravimetric soil moisture. It is important to keep all of these variables in mind when developing sediment transport models. Bagnold (1941) introduced an equation to

quantify the amount of sediment that could be transported by wind as a function of shear stress and found that sediment transport could be expressed as:

$$q = C \left(\frac{d}{D} \right)^{0.5} \frac{\rho}{g} u_*^3 \quad (4)$$

where d/D represents a ratio of the mean diameter of the experimental sand to a 'standard' grain diameter of 0.25 millimeters. C represents a coefficient that represents the degree of sorting for the experimental sediment where so that:

- $C = 1.5$ for nearly uniform sand
- $C = 1.8$ for naturally graded sand
- $C = 2.8$ for poorly sorted sand
- $C = 3.5$ for pebbly surfaces

Studies regarding sediment transport equations continued, including work by Zingg (1953) and Kawamura (1951), which helped outline fundamental problems with the Bagnold (1941) and Zingg (1953) approach. Both equations omit shear threshold velocity (u_{*t}) for the given sediment size, meaning these equations calculated transport rates for velocities that were too slow to initiate transport. Lettau and Lettau (1978) (for example) rectify this problem in the equation:

$$q = C \left(\frac{d}{D} \right)^n \rho u_*^2 (u_* - u_{*t}) \quad (5)$$

where the n exponent can range from 0.5-0.75.

These equations are useful in locations where there is no active sediment transport during the study period (which occurred for this particular study) or where delicate instrumentation like hot-wire anemometers which would be damaged from sand grain impact are being implemented. They may also serve as estimations for sediment transport in regions where only wind data has been collected as demonstrated by Wasson and Nanninga (1986).

2.5 Defining the Density of Vegetation

Botanists, ecologists, and geomorphologists alike have measured plant density for a given region using two methods. The line transect method uses a guide such as a measuring tape, laid out over a given area so that the species, number of plants and the transect portion occupied by each type of plant that intersects the line can be recorded (Cummings and Smith, 2000). After the completion of a representative number of transects over a study area, the density of each plant species can be determined (Cummings and Smith, 2000).

The quadrat method is the most commonly applied technique. An area of known size, generally one square meter, is placed within the study site and the number of plants falling within the plot are counted or a visual estimation of percent cover is recorded for the plot area. This is repeated several times for the study site by moving the 1 meter² plot along a transect or grid pattern through the study site. Each plot is recorded and averaged in order to calculate the density of plant cover for that region (Gardiner and Dackombe, 1983; Cummings and Smith, 2000).

These methods however, may be prone to subjectivity as they rely entirely on personal observations by the researcher, thus introducing a potential for bias as well as problems regarding repeatability. Different observers may have different viewpoints as to what constitutes 24 percent cover and what is 26 percent cover. Although small, these differences accumulate throughout the study site and may result in very different outputs of cover, and may be highly problematic in applied management studies where small differences in one parameter may result in a highly varied output in another parameter. As a result, some workers began to approach the methodology of measuring plant density from another perspective, and began measuring the volume of space the obstacles

occupied over a total surface area (*for example see* Kutzbach, 1961). This ideology initiated a new method of determining roughness density within an aeolian context that was more objective, as it removed observation bias and relied on the roughness elements physical attributes.

2.6 Density Calculations of Vegetation for Aeolian Studies

Density calculations for roughness elements had to follow a more strict protocol than methods generally adopted by ecologists and botanists, especially when trying to understand the complex mechanics of how these obstacles altered wind flow. Lettau (1957), followed by Kutzbach (1961) developed a new, and possibly more accurate method of measuring vegetation cover. This method involved deriving the total volume of the obstacle and applying it over the entire study area, later expressed by Raupach (1993) as:

$$\lambda = bh / D^2 = nbh / S \quad (6)$$

where b is equal to the diameter of the object and h is the height of the object (as seen by the oncoming wind flow), n is the number of objects occupying the surface area S .

Termed “roughness density”, λ is an expression of the frontal area of each obstruction per unit ground area (Lettau, 1969) (Figure 2.6a). The measure of roughness density was later adapted to suit vegetation in a measure most commonly referred to lateral cover (L_C) which can be represented by:

$$L_C = DA_S \quad (7)$$

where

$$D = \frac{n}{S} \quad (8)$$

A_s represents the frontal-silhouette area, a two-dimensional representation of the plant form that the wind ‘sees’; n is the number of roughness elements and S is the total surface area occupied by the roughness elements (Figure 2.6b).

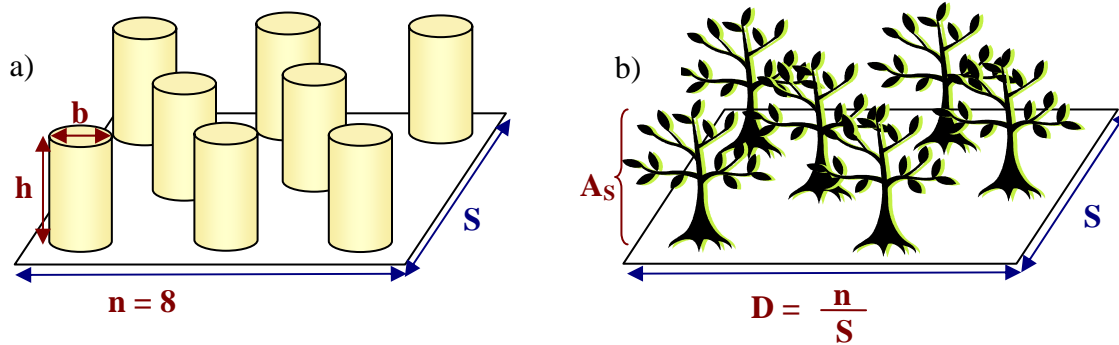


Figure 2.6: Density calculations for roughness elements over a specified surface. a) demonstrates roughness density as calculated using solid elements and b) is lateral cover the method to calculate vegetation cover over an area.

There have been recent attempts within the literature to find new, more accurate methods of determining plant density that go beyond a simplified two-dimensional representation and account for the dynamic nature of vegetation. Wasson and Nanninga (1986) used sketches of the vegetation to delineate a total vegetation cover for areas roughly equal to 1000m². A study by Arens, *et al.* (2001) calculates the lateral cover of an entire bundle of reed stems as well as the lateral cover of each individual stem comprising the bundle. Other methods, like the one demonstrated by McDonald, *et al.* (1998), follow a similar approach to the original lateral cover method but also attempt to account for the two dimensional nature of vegetation by including a two-dimensional, plan-form representation of plant cover into the equation. Kuriyama, *et al.* (2005) combine the traditional line-transect method with the lateral cover measure using bamboo fences to quantify a measure they define as a vegetation index. Leys (1991), following a study conducted by Fryrear (1985), used the dry weight of vegetation as a means of

determining percent cover. Excluding the latter example, most of the approaches to quantifying vegetation density have remained within the general paradigm first quantified through the evaluation of solid elements.

Only one approach really stands out in the literature for attempting to capture the 3-dimensional aspect of vegetation and account for its variability in size, shape and porosity. The study conducted by Grant and Nickling (1998) used an artificial scots pine and submersed it in water to determine the total volume of the tree. Although the purpose of this study was not to identify the differences in density calculations, an indirect comparison may be made through their interpretation of volumetric and optical porosity, which requires a two-dimensional representation of the plant form in a similar way to lateral cover. The results indicate that as optical porosity increases, volumetric porosity increases exponentially (Grant and Nickling, 1998). It must be stated again that this is not a measure of lateral cover versus volume; however, the trend, which may be indirectly related, indicates that using only a two-dimensional representation of the plant form may be a significant under-representation of the plants potential to extract momentum.

2.7 Key Concerns Regarding Current Practice and Model Applications

Based on the previous discussion, there seems to be a significant problem in the appropriateness of measures used to quantify vegetation density in field investigations. Relying on constant variables and equations that simplify reality is becoming an issue of greater concern for many aeolian geomorphologists or other disciplines concerned with analyzing flow mechanics and velocity profiles as a means for determining u_* and z_0 values (Bauer, *et al.*, 1992). As described earlier, many parameters for analyzing fluid mechanics are based upon determining variables under perfect, log-linear conditions of

boundary flow that fit within the Law of the Wall (Bauer, *et al.*, 1992). Operating within these parameters can offer a high degree of variability and uncertainty for output results. This may be emphasized when analyzing the predicted rate of sediment transport which generally requires the cube of the calculated u_* value, meaning that a 10% calculation error of u_* may result in a 30% error for sediment transport (Bauer, *et al.*, 1992).

Defining vegetation cover by using a two-dimensional measure like roughness density over simplifies natural plant morphology, and likely underestimates actual plant coverage. Therefore, it may be suggested these methods also have a high probability of underestimating potential flow reduction. This is especially apparent when considering the flexibility of plants and how the frontal shape and porosity change with increasing wind speed (Gillies, *et al.*, 2002). The frontal silhouette area used to define the portion of the plant that the wind ‘sees’ is a static parameter and is unable to compensate for changes in vegetation as it bends or moves in wind. A static parameter lacks any potential of accounting for the variability in the changing surface area exposed to wind flow as the plant bends and changes its morphology during wind flow events. As discussed earlier, there have been recent attempts to modify this static parameter by Grant and Nickling (1998) and McDonald, *et al.* (1998), however, most vegetation studies use frontal area to define vegetation cover (Wasson and Nanninga, 1986; Arens, *et al.*, 2001).

Extensive studies have been completed regarding the parameters of flow separation around solid elements both within field and laboratory environments. These studies include the examination of size, shape, and spatial arrangements and how the flow field is altered by these specific variations. Although studies have been completed regarding flow through *in situ* vegetation (e.g. Hesp 1983), there have been no direct

attempts to manipulate natural vegetation to better understand how flow conditions are altered by variations in shape, size, height, spatial arrangement, and density.

Models that concern drag and shear stress partitioning may be rendered impractical for management application as they have been created using simple, non-erodible shapes that are not realistically representative of the characteristics of natural vegetation, as discussed earlier. Marshall (1971) acknowledges this shortcoming in his application to measuring drag over various roughness densities stating that the cylindrical elements used in his studies cannot take into account the permeability nor the flexibility of natural vegetation even though this study is implied to be directly relatable to a natural setting. Although Marshall (1971) clearly states the inadequacy of using solid elements, there appears to be a continued trend in examining how wind flow and wake development is altered by these solid, simple shapes (*for example see* Raupach, 1992; Al-awadhi and Willetts, 1999; Choi and Lee, 2000; Crawley and Nickling, 2003). Although these studies provide a significant amount of information regarding the general mechanics of flow, they lack the fundamental principals regarding wind flow through natural vegetation. This limits the overall productivity of effective model development when using these applications, specifically models developed for management purposes. Using models developed in simulated environments tends to oversimplify the true nature of the geomorphological processes (Haff, 1996). Using these oversimplified models with constants that do not apply uniformly natural environments as a basis for a management projects may prove to be costly errors.

CHAPTER 3: METHODOLOGY

This purpose of this chapter is to outline each of the methods utilized during this study. Description of each of the methods conducted both in the field, as well as all statistical and data analysis conducted is provided within this chapter.

3.1 Study Site

Research was conducted along the Texas Gulf Coast, within Padre Island National Seashore, a park established within a large barrier island that extends 182 kilometers along the northwestern shore of the Gulf of Mexico (Figure 3.1). Set aside in 1962 to preserve the natural conditions of the region, Padre Island National Seashore is 129 kilometers in length and varies in width between one to four kilometers (Weise and White, 1980).

The beach is dissipative with a three-bar, longshore bar and trough morphology. Sediment is very well sorted and consists of fine to very fine quartz grains with a mean diameter of 0.14mm. Tides within the region are microtidal (with a typical range of roughly 0.4 meters) and are dominated by a diurnal cycle although semi-diurnal events do occur (Weise and White, 1980). The backshore is roughly 30-35 meters wide and is backed by a consistent foredune that ranges in height from six to twelve meters with its maximum height reaching just above 15 meters (Weise and White, 1980). Vegetation along the foredune ridge varies relative to elevation. Where morning-glory (*Ipomoea* spp.) and sea purslane (*Sesuvium portulacastrum*) define the lower portions of the dunes on the leeward side of the ridge, middle and higher elevations are typified by bitter panicum (*Panicum amarum*), sea oats (*Uniola paniculata*), and gulf croton (*Croton punctatus*) (Weise and White, 1980). Landward of the foredune, the barrier is well vegetated and is comprised of relict nebkhas, relict overwash fans, and intermittent low-

lying marsh areas and re-vegetating transgressive dune fields. A mix of tidal flats and marsh occurs on the lagoon side of the barrier.

The regional climate is generally characterized by subtropical and semi-arid conditions with an average summer temperature of 35°C, an average winter temperature of 13°C, and a mean annual rainfall of about 73.66 centimeters (Weise and White, 1980). Dominant winds are from the southeast and blow almost directly onshore however, during the winter months when a polar front moves south, the dominant wind direction may shift to the offshore direction (Weise and White, 1980). During the time of study, winds were consistently onshore with little fluctuation in direction.

The study site comprised a flat beach at the toe of the foredune in the no-drive-zone of the park near the Park Rangers headquarters as shown in Figure 3.2. There was little to no rain for the entire study period. Wave-run up from Hurricane Dennis saturated the study site, reducing the prospect of any sediment entrainment, however, it was unlikely that sediment entrainment would have occurred due the beach composition. No sediment movement occurred on the beach region for the entire study period.

3.2 Field Methods

3.2.1 Vegetation Density Measures

- **Artificial Vegetation**

Artificial vegetation was created using wooden dowels (0.6 centimeters in diameter and cut into 22 centimeter lengths), plastic zip-ties, and electrical tape. The locking mechanisms were removed from the zip-ties so that each was the same length. Each length of dowel had for zip-ties fastened to it roughly 5.5 cm from one end of the

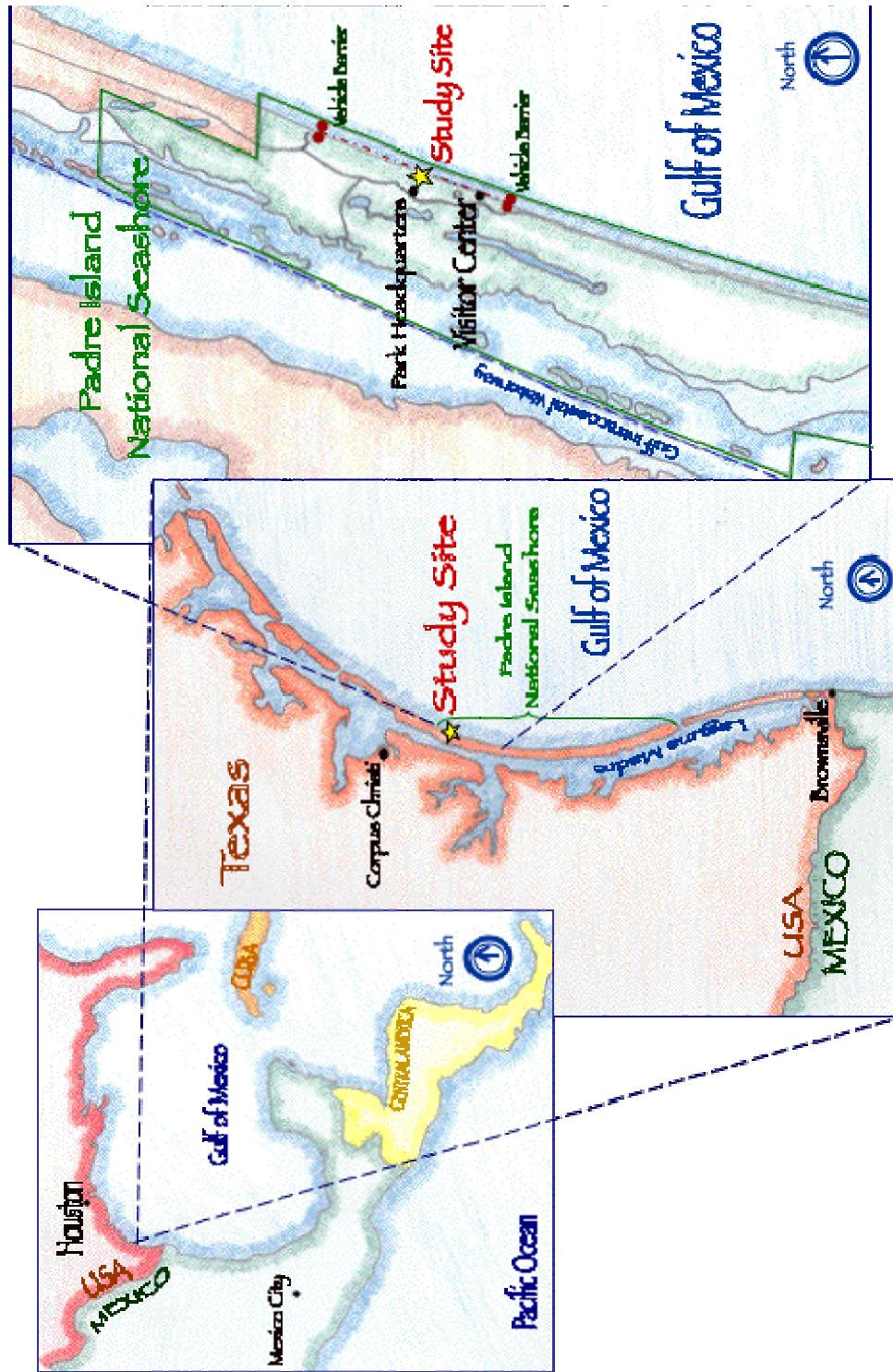


Figure 3.1: Map of study area relative to the Gulf Coast of Texas, USA. Far right image illustrates location of study site relative to other features in Padre Island National Seashore.



Figure 3.2: Study site situated at the end of the laneway to the Park Headquarters at Padre Island National Seashore, Texas, USA. Image is looking inland from the beach.

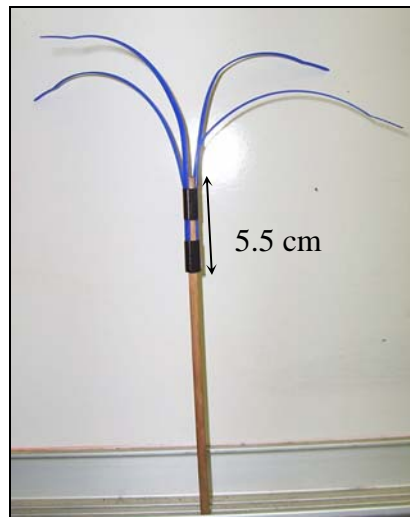


Figure 3.3: Artificial vegetation utilized for this study. The dowel making up the bulk of the stem is 22cm in length. The ‘leaves’ are made from plastic zip-ties that have been attached using black electrical tape.

dowel. The zip-ties were then secured with electrical tape. Figure 3.3 is an illustration of a completed artificial plant.

Due to the nature of this experiment, knowledge of the plant density was critical. This required determining how many plants were needed to reach a specific density

interval for the experiment. It was determined that by estimating the volume of a single artificial plant and applying it to the total area of the experiment site, the percentage of cover could be easily determined. Calculating the volume of each roughness element and applying it to the total surface area of the experiment site was also completed in the same manner for the natural vegetation as well as the solid, wooden cylinders.

A total of ten artificial plants were measured in order to calculate a mean volume for subsequent volume calculations. Only ten plants were used because there was very little variation in the size or dimensions of the artificial plants. Volume was calculated by first using a ruler to measure the surface area (determined by measuring the length and width of each leaf) and depth of each of the zip-tie ‘leaves’ as well as the stem diameter and height. Height measurements were taken from the point at which the artificial plant would sit above the ground. This is demonstrated more clearly in Figure 3.4. After completing the measures for all ten artificial plants, the volume for each was calculated and then each of the volumes were averaged to determine the average volume of the artificial plants. Calculating the average volume of an artificial vegetation may simply be represented as:

$$V_L(4) + \pi r^2 h \quad (9)$$

and V_L is simply the volume of each leaf component:

$$V_L = lwd \quad (10)$$

where r is the radius of the stem, h is the height of the above ground portion of the stem. l is the length of the leaf, w is leaf width, and d is the leaf thickness. These parameters are more clearly demonstrated in Figure 3.4.

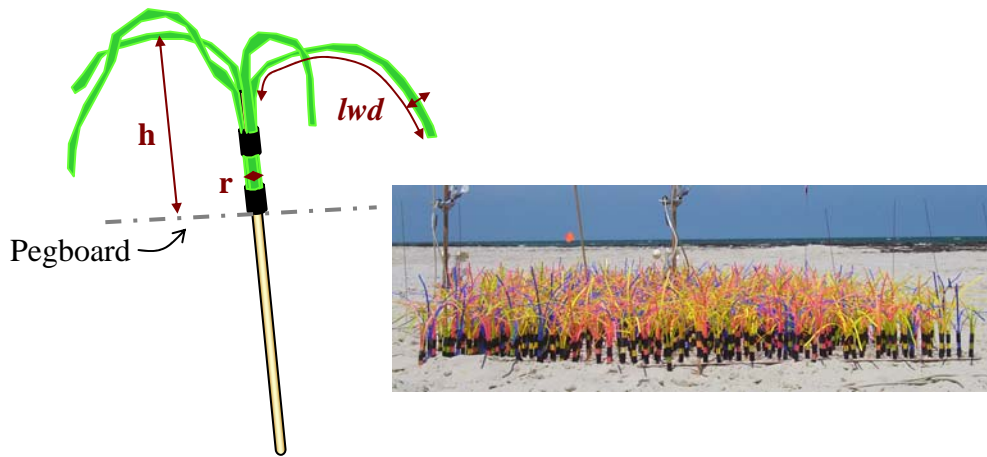


Figure 3.4: Depiction of volume calculation for artificial vegetation. Where r is the radius of the stem, h is the height of the above ground portion of the stem. l is the length of the leaf, w is leaf width, and d is the leaf thickness. Illustration of artificial plant outlines the length, width and depth measures of the leaves. Note that the diameter was taken to include the zip-tie width and height of the vegetation was taken from the top of the plant to the point where it sat within the peg board.

- Natural Vegetation

The natural vegetation was collected off site as disturbance vegetation within the park is prohibited. Only *Panicum amarum* was collected for this study. Vegetation was clipped from the tops of each grass shoot so that the height of each plant was roughly the same for each clipping. Also, this helped to regulate the number of leaves that were on each stalk so that no natural plant in the study had less than two leaves or more than four leaves, with the majority having three or four leaves. Only fresh cuttings were used and as the natural vegetation began to dry out, it was removed and replaced with new, fresh stalks. During the high temperatures in the afternoon, this sometimes meant replacing all the vegetation after only two runs.

Density calculations for the natural plants were conducted in a similar manner to the artificial plants, however, due to increased variability between the plants, 30 samples were measured to generate an average volume. Calculating the volume of each natural

plant was somewhat labour intensive because each leaf had a slightly different morphology and each terminated into a point. To compensate for the irregular shape, the leaf was broken down into segments and then measured. Sketches of ten random leaves were also made to verify that the total surface area matched the sum of each of the segmented measures. This provided verification of the surface area calculations that were completed in the field using the segmented components. There was little to no variation between the surface area of the sketched leaf and the sum of the leaf segments. Measuring the surface area and thickness of each of the leaf components, calculating the volume of each segment, and then summing each together provided the total volume for each leaf. This was completed for every leaf on twenty-five stalks. The stem of each plant was also calculated by breaking down the stalk into components, measuring their height and diameter, calculating the volume of each component and then summing all the sections together.

- Wooden Dowels

Wooden dowels were also used to provide a basis for comparison against previous studies that implemented solid cylinders as roughness elements. Each dowel was 2.5 centimeters in diameter and was cut into ten-centimeter increments. Measuring the height and diameter of a random selection of dowels and applying the basic formula calculated the volume of the dowels:

$$V = \pi r^2 h \quad (11)$$

where r is the radius of the dowel and h is height. In this case, because all the dowels were identical, only three random dowels were measured and recorded to test for variability in volume. There was no difference in volume between the three dowels.

3.2.2 Applying Vegetation Volume to Density Cover

Once the mean volume of each of the roughness elements was computed, percentage cover was determined by applying the volume of each roughness element to the defined pegboard area onto which the plants were placed. The study area was divided into four equal sections that each measured 1.49 square meters. The layout of the specific study area will be discussed later. By working out the percentage of cover that one plant occupied, it was possible to determine exactly how many roughness elements were required to reach a specific density. This was completed by applying the volume of one plant individual over the total surface area of the study site (1.49 m²) and determining the percentage of cover by a single plant. Once the percent cover of one plant was determined then the total number of plants required for each incremental increase was determined from this value.

3.2.3 Pegboard Arrangement

In order to systematically plot vegetation to match the desired density for each run, four pegboards each measuring 1.22 meters by 1.22 meters, were placed flat on the beach surface. Pegboards were used because the holes provided a base to insert and support the stalks of the natural and artificial vegetation and because of their standard hole arrays. Each pegboard was aligned next to the other so that the total length of all the boards together ran perpendicular to oncoming wind flow. Each of the four sections of pegboard were divided into equal-sized quadrates using the hole spacing as a guide. First, each of the boards were divided into squares that measured twelve holes by twelve holes, giving each board a grid of 16 equal sections. These 16 sections were then split into smaller squares of six holes by six holes so that all each of the four pegboard were

evenly divided into 64 sections and had an equal number of peg-board holes available for the purpose of arranging vegetation.

Although Marshall (1971) determined that the spatial arrangement of roughness elements on the surface does little to alter the shearing stress upon the surface, it was decided that plant placement should be somewhat randomized to represent a more natural growth pattern. In order to ensure coverage of the whole pegboard area, the placement of the individual plants was randomized within the smaller 6 x 6 hole sections. Within these sections, a random number generator was used to determine the placement of vegetation so that each hole was assigned a number and vegetation was plotted into the corresponding hole, thus allowing for a “controlled” randomized distribution.

The peg boards were limited in size and allowed for maximum coverage of the available area. They also eliminated the potential for edge effects or flow channelization near the anemometers, thus providing a more representative measure of wind velocities with changing percent cover. With each addition of percentage cover, a new random number generation was used. If there was an overlap in values and the placement of one plant corresponded to a location that had already been filled, the next number in the series was used.

Because the diameter of the dowels was considerably larger than the natural and artificial vegetation, placement was predetermined using the same method as described above and the selected holes were pre-drilled so the dowel could easily be inserted into the pegboard. In the case that dowel hole placements were too close to each other, the next value in the random number generator was chosen. Implementation of wooden dowels as a point of comparison was intended for this study, however, data collected using the wooden dowels was eliminated due to circumstances beyond the researchers

control. Therefore they are only used as a method of density comparison as no useful wind data was collected from the experimental runs in which dowels were utilized.

3.3 Experimental Runs

Percentage density cover was calculated by relating the volume of a single plant to the total board area in order to determine the percentage of cover by a single plant. This value was then used to determine how many plants would be required for each five percent density increment. Several different arrangements for both natural and artificial vegetation were completed for comparison reasons. For the first series of incremental density runs, both the fresh vegetation and the artificial vegetation were examined independently from each other over two pegboards. During these runs, three anemometer masts were used. Mast 1 (M1) was placed 1 meter upwind of the pegboards in the free stream where there was no obstruction to oncoming flow. Mast 2 (M2) was located in the most central location of the pegboards, 65 cm from the windward edge of the boards. Mast 3 (M3) was located in the lee of the plants roughly 5 cm from the back edge of the board. Figure 3.5a illustrates this set up. M1 had three miniature-cup anemometers set at heights of 8 cm, 50 cm, and 90 cm above the bed. M2 and M3 each had 4 miniature cup anemometers placed at heights of 8 cm, 25 cm, 50 cm, and 90 cm above the bed. Artificial vegetation was recorded first, starting at 5% cover and increasing incrementally up to 66% density cover as based upon volumetric calculations. Each run was 10 minutes in length and replicated. This set up was repeated for the natural vegetation, beginning at 5% and increasing to 70% density cover. Wind direction was monitored continuously throughout all of the runs to ensure the fetch length remained continuous throughout each of the runs.

The second arrangement of natural and artificial vegetation plots is demonstrated in Figure 3.5b. This layout used all four pegboards. Two adjacent boards were covered with artificial vegetation and the remaining two boards were covered with natural vegetation. The anemometer arrangement was altered so that M2 and M3 were both placed in the leeward edge of the boards with M2 falling directly center of the artificial plants and M3 being centered in the wake of the natural vegetation. M1 remained in its windward location centered 1 meter upstream of the four pegboards and was centered between the four boards. The anemometer cup heights for each mast remained the same as the first experimental arrangement.

3.3.1 Natural Vegetation Plots

While collecting natural vegetation for plotted runs, five random sample-plots, each measuring 1.22m^2 (equal to the peg-board area) were sectioned off. Each of the plots contained only *Panicum amarum* and individual plants were counted for each plot to determine the natural growing density of the vegetation on an established and stabilized foredune.

3.4 Data and Statistical Analysis

3.4.1 Qualitative Analysis

In order to develop a comparative examination of the differences in overall boundary flow development between the artificial and natural vegetation simultaneous readings were taken and manipulated so that wind speeds read as a total percentage of flow. This was completed by normalizing the data to a single control tower (M1) and using the top-most anemometer at 90cm to represent 100 percent velocity. All changes in velocity for each run relative to vegetation type, changes in density, and height above the bed were compared to this 100 percent value independently. Visualization of the flow in

this manner allows for some interpretation as to how the wind flow characteristics vary between the artificial and the natural vegetation.

3.4.2 Calculating Lateral Cover

Lateral cover was derived for each run as a means of comparison between the volumetric density calculations and the lateral cover method of calculating vegetation density. Lateral cover may be expressed as:

$$L_C = DA_S \quad (7)$$

where

$$D = \frac{n}{S} \quad (8)$$

A_S represents the frontal-silhouette area, a two-dimensional representation of the plant form that the wind ‘sees’; n is the number of roughness elements and S is the total surface area occupied by the roughness elements

In order to determine the frontal-silhouette area of the natural and artificial vegetation, digital images were taken of a random sample of both natural and artificial vegetation types. Each image in this analysis was taken directly upwind of the vegetation to ensure an accurate representation of the total frontal area. Individual plant selections were taken at random from the image and isolated. Once certain plant individuals were isolated, the image was overlaid with a fine grid pattern of equal spacing. Once the grid was applied, a reference point within the image was used as a basis for determining the ratio between the size of the grid and the actual size each square represented in reality. Once this ratio was established, the total number of squares occupied by each plant individual in the image was counted and then converted into an actual frontal area as based on the size ratio. This process was repeated for several individual plants for both natural and

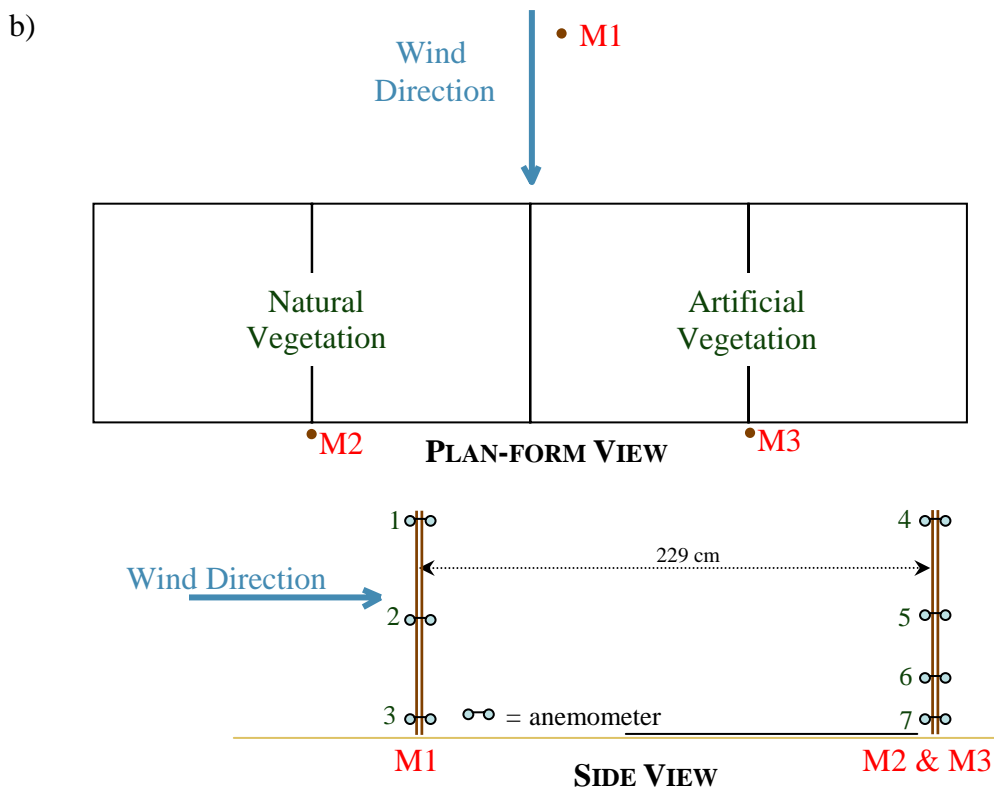
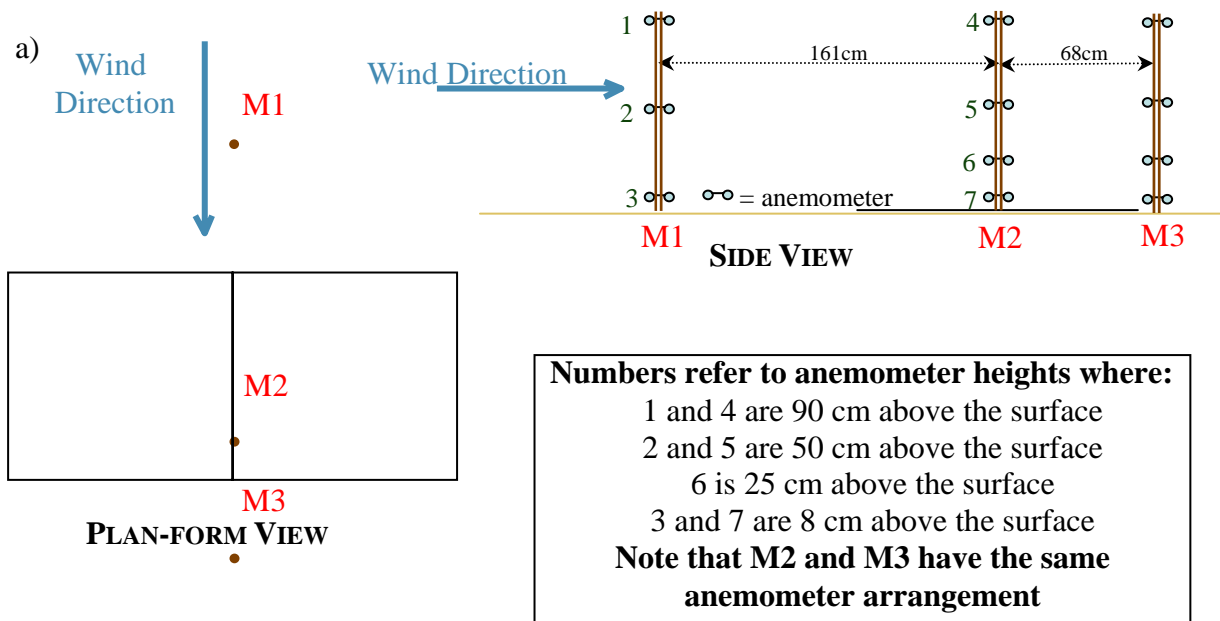


Figure 3.5: Pegboard arrangement for study site. a) Plan-form and side view of first pegboard arrangement where both artificial and natural vegetation velocity profiles were recorded independently of each other. b) Plan-form and side view of second pegboard arrangement where artificial and natural vegetation velocity profiles were recorded simultaneously using the same reference tower (M1). Arrow indicates oncoming wind direction. M1-M3 indicates anemometer mast location.

artificial vegetation as well as the dowels and then averaged to provide a general representation of each of the three elements. Once the frontal area of each plant was determined, the values were simply plotted into the Equation 7 to generate a lateral cover that could be associated with each volumetric density calculation.

3.4.3 Quantitative Analysis

All data are re-organized according to the calculated lateral cover for quantitative analysis. This was completed to provide a direct comparison between the volumetric and the lateral cover methods of defining percent cover of vegetation. Because the initial experimentation used the volumetric method for calculating plant density rather than the lateral cover method, re-organizing the data accordingly resulted in a reduction of the initially proposed range of density covers. This accounts for the reduction of data in the following result chapters for all lateral cover representations. The table that illustrates the reduction of the dataset in its entirety to match lateral covers can be found in Appendix Table B.

- Regression Analysis Between Anemometer Masts

Due to natural fluctuations in wind speeds, specifically the observed increase in onshore wind velocity throughout the day, the Law of the Wall could not be readily applied to determine U_* values for the study site as vegetation density increased. In order to overcome this variability of wind flow between runs for both natural and artificial vegetation, anemometer masts M1 and M3 were compared at corresponding heights starting with the highest anemometer set at 90 centimeters above the bed in order to calculate any variability between the two masts for each run. A regression analysis between the two masts at 90 centimeters for all runs was taken as a measure for variability between each of the runs.

Similarly, wind speeds recorded at 50 centimeters above the bed were also compared between M1 and M3 for natural and artificial vegetation runs. A regression analysis between the two anemometers at this height was conducted for all completed runs. A regression of the absolute difference in wind velocities between M1 and M3 for anemometers at 50 centimeter heights were also completed to draw out some of the outliers and variability found in the residual output of the regression.

- Momentum Flux Calculations

The momentum flux (M) was calculated by comparing the velocity profiles from M1 and M3 for each vegetation density independently. Due to the regression results between anemometers set at 90 and 50 centimeters, only wind velocities at 50 cm above the bed and lower were included in calculating momentum flux. This is because the results indicate there was no significant difference in wind speed between the two towers for the anemometers set at these heights. A velocity profile for each density was constructed, however, the independent (height above the bed) and dependent (wind velocity above the bed) variables on each axis were arranged so that proper analysis could be completed. This is more clearly demonstrated in Figure 3.6 where Figure 3.6a represents the usual display of a velocity profile and Figure 3.6b shows the same profile with the axis rearranged for analysis. Once plotted, the total area under both of the curves representing M1 and M3 were calculated using the Method of Polygons which is illustrated in Figure 3.7.

Once the area under each curve was calculated, the difference in area between the two curves was recorded. Estimations of momentum are based upon the equation demonstrated by Allen (1985) where momentum flux equals:

$$M = \rho U^2 \quad (12)$$

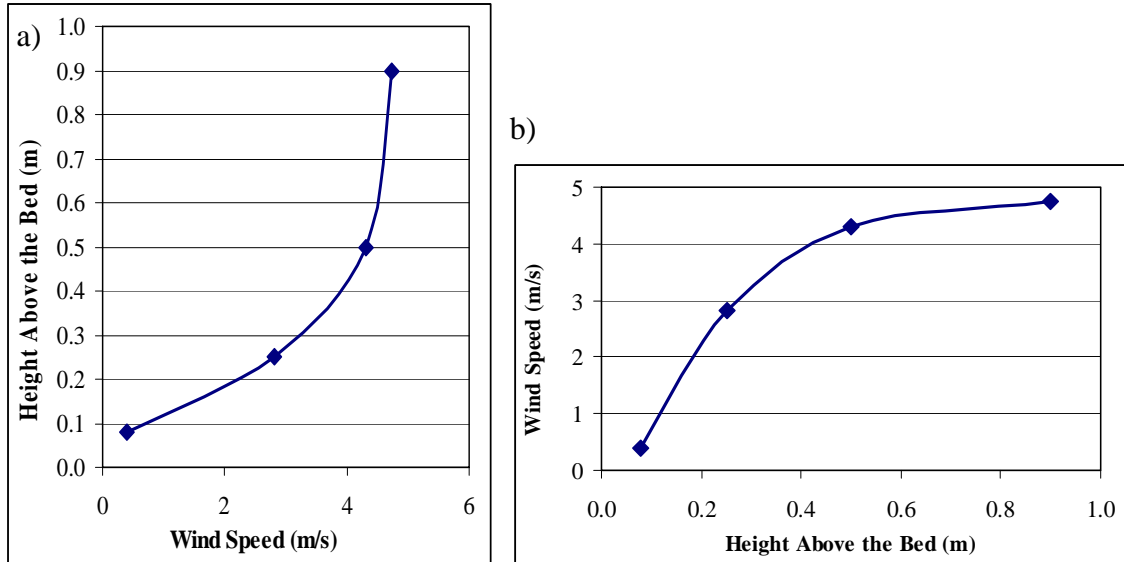


Figure 3.6: Transition of velocity profiles from standard to normal axis. a) illustrates how velocity profiles are most commonly demonstrated within the literature b) is the same profile rearranged so the independent and dependent variables are properly arranged.

where M is momentum flux. However, this equation only accounts for horizontal change in momentum. Therefore, using the entire area between velocity profiles to determine the estimated momentum flux required a modification of the original location to:

$$M = \frac{A_C \rho U^2}{A_D} \quad (13)$$

where A_C is the area between the velocity profile curves (m^2/s) and A_D is an area based on the length of the peg board. This method provided the force exerted on the surface in Newtons (kg/s^2). In order to derive an estimated momentum flux for each vegetation type, the resultant extraction of force between each set of curves was then divided by a unit area of 1.22m^2 . This area is the length of the peg board (1.22m) multiplied by a 1m width. Following this method not only provides a resultant vertical momentum flux but also represents the momentum extraction from the vegetation in a horizontal vector.

- Predicted Sediment Flux Calculations

Once the momentum flux calculations were completed, these values were used to determine the shearing velocity (U_*) and shear stress (τ_o) for each run for both lateral cover and volumetric density measures using the following equations respectively:

$$U_* = \sqrt{\frac{M}{\rho}} \quad (14)$$

It is acknowledged that these calculations are based upon momentum flux and therefore incorporate any potential errors that may have been created in the determination of the momentum flux itself. However, for the purposes here, these potential errors are considered to be incidental and it is unlikely that these errors would greatly distort the general trend of the data.

Because there was no sediment movement during the length of this study, an equation presented in a paper by Lancaster and Baas (1998) was used to determine the predicted sediment flux in varying plant densities. :

$$q = 300(u_* - u_{*t})^3 e^{-25\lambda} \quad (15)$$

and

$$U_{*t} = A \sqrt{gD \frac{\sigma - \rho}{\rho}} \quad (16)$$

where A is an empirical constant usually assigned the value of 0.1, σ is the sediment density (2643 kg/m³ for quartz sand found at the study location), and λ represents a measure of surface roughness.

It must be emphasized here that the Lancaster and Baas model was chosen because it provided a means of estimating the sediment flux as a function of the vegetation cover over the study site (Lancaster and Baas, 1998). There has been no

attempt to test this equation for accuracy or precision, nor was there any attempt to compare to output of this particular model to other models that have been developed to account for sediment flux over vegetation. This model was chosen solely for its ease of use and that it required variables that could be determined from the data collected in this experiment without substituting for any unknown variables or constants.

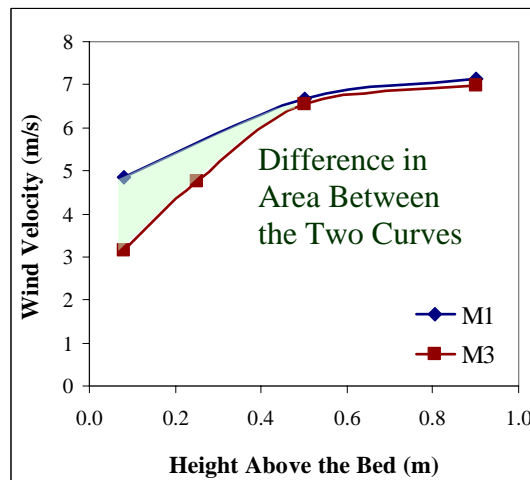
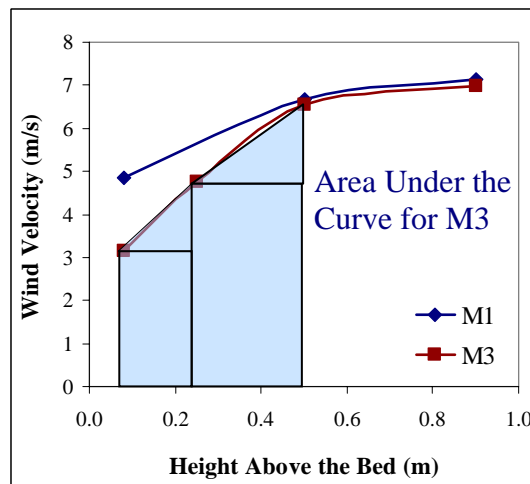
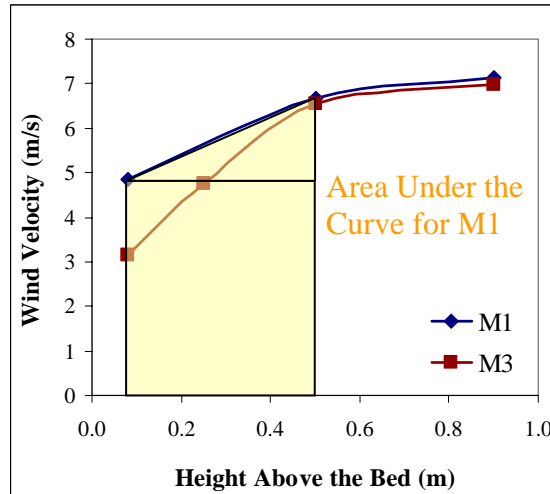


Figure 3.7: Process of calculating momentum flux using the M1 and M3 velocity profiles. Red and blue areas under the corresponding line, show the simplified shapes used to calculate the area under each of the velocity curves. These areas were then subtracted from each other to determine the purple area shown in the bottom graph. The green area is an example of the area used to calculate momentum flux.

CHAPTER 4: VISUAL COMPARISON OF FLOW CHARACTERISTICS BETWEEN TWO VEGETATION TYPES USING CONTROLLED DENSITY INTERVALS

This chapter presents data on the dynamics of wind flow in plots of both natural and artificial vegetation with varying densities. In the following, wind speed are used to show the different flow patterns in natural and artificial vegetation. More specifically, this chapter attempts to outline the variation of flow patterns between natural and artificial vegetation and how these plant types alter boundary layer flow. The reasons for the variation in flow patterns from both increasing density as well as between each vegetation type are also outlined within this section.

4.1 Wind Flow in Artificial and Natural Vegetation

Figure 4.2 illustrates the wind speed profiles for artificial and natural vegetation. These are presented as a percentage of velocity where the top-most anemometer on the control tower (M1) represents 100 percent of oncoming wind speed. All other wind-speed readings for each anemometer are based upon this reading. These profiles were recorded following the second study site arrangement as illustrated in Figure 3.7b from the Methodology Section. Each of the following velocity profiles in Figure 4.2 corresponds to the vegetation arrangements correspond to the images in Figure 4.1.

There are several general points that can be drawn out of the velocity profiles shown in Figure 4.2. The most obvious is that artificial vegetation reduces oncoming flow velocity at the bed more so than the natural vegetation for the same volumetric density. This may be explained by the images shown in Figure 4.1 where it is clearly shown that there are far more artificial plant individuals for each density compared to the natural vegetation plots. This and other key points of the wind speed profile will be discussed further respective of each vegetation type.

4.1.1 Artificial Vegetation

Figure 4.2 indicates that the greatest overall reduction of velocity occurs between the 10 percent and 15 percent density with an overall reduction of roughly 19 percent of flow at the bed. This provides insight as to how even the addition of a few roughness elements to the oncoming flow can reduce velocity at the bed. This, however, may also be a result of the anemometer being directly in the wake of a select few plants, thus causing a large reduction in the flow. The same might be said for the sudden increase in velocity at the bed for artificial vegetation that can be seen between the 25 percent cover and the 30 percent cover. A slight shift in wind change is noted between these two runs. Although the shift in wind direction maintained the same fetch length across the vegetation, it is possible that this shift resulted in a channelization of flow through the vegetation that is not witnessed in the other velocity profiles. This channelization may be responsible for the increasing wind speed recorded by the leeward anemometer for this particular run.

There is also a noticeable reduction in wind flow at the bed as density increases from 30% to 40% and again from 40% to 50% vegetation cover. These decelerations in flow velocity suggest that these densities may have a positive impact on the potential for sediment accumulation by means of flow reduction at these particular vegetation densities. This is in general agreement with the literature which site a range of 15% density cover to 50% density cover for the ideal planting density to collect sediment through wind flow reduction (Wasson and Nanninga, 1986; Lancaster and Baas, 1998).

Reduction in flow velocity follows a distinct pattern as planting density is increased. Flow reduction occurs mostly close to the bed, with wind speed increasing



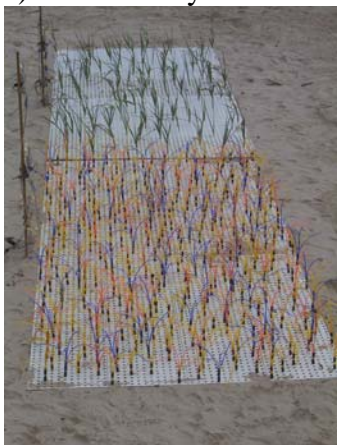
a) 10% Density Cover



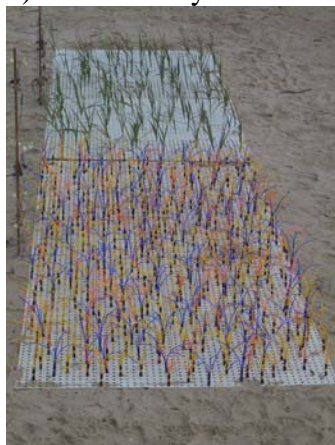
b) 15% Density Cover



c) 20% Density Cover



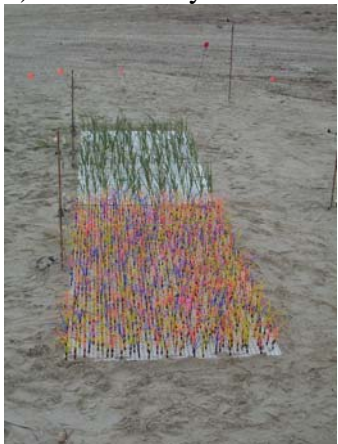
d) 25% Density Cover



e) 30% Density Cover



f) 40% Density Cover



g) 50% Density Cover



h) 60% Density Cover

Figure 4.1: Incremental increases of equal density for both natural and artificial vegetation for direct comparison. These densities were plotted according to the density calculations for each vegetation type. The artificial vegetation is the multi-coloured stems and is always in the foreground of the images. The natural vegetation is situated in the background.

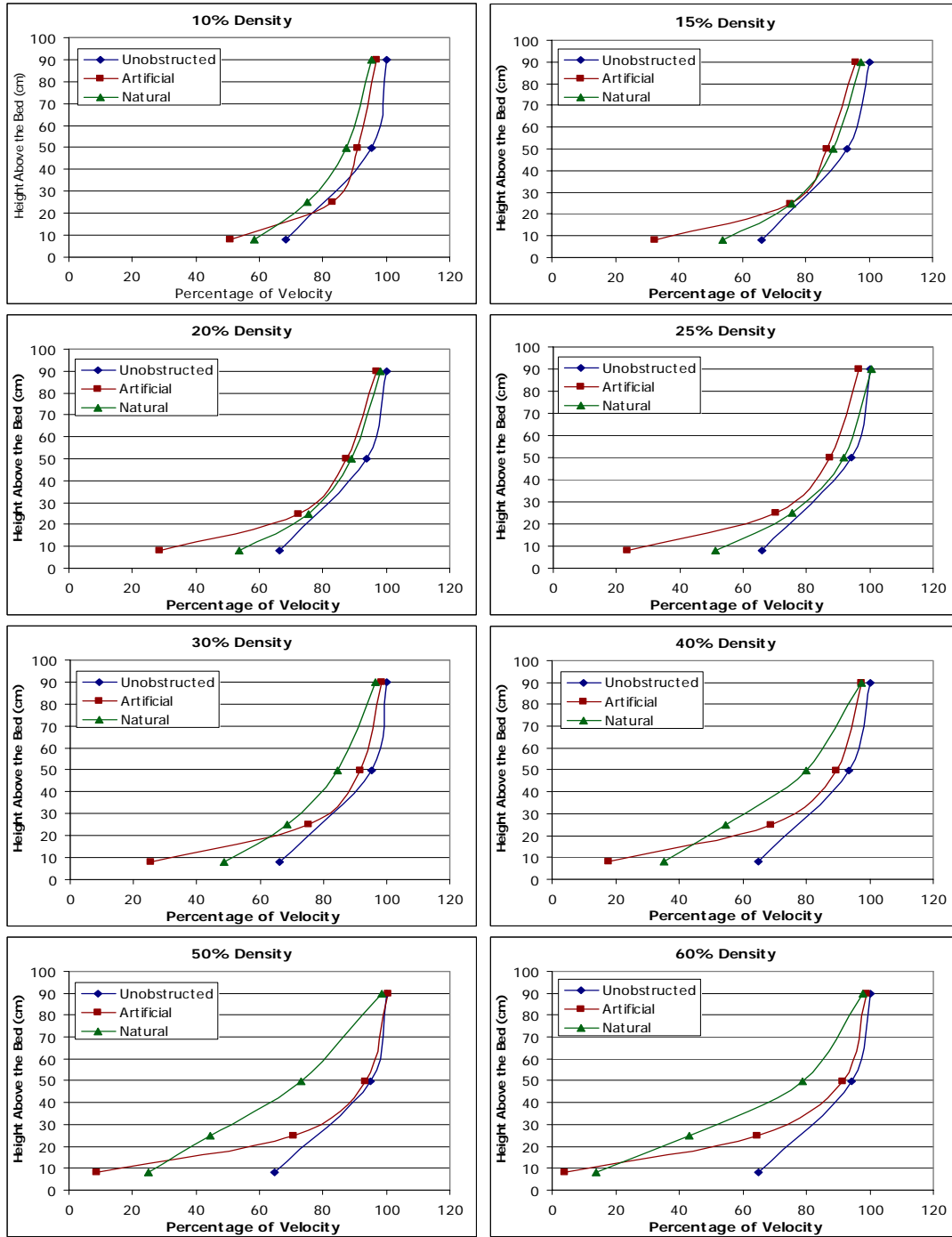


Figure 4.2: Percentage of wind speed profiles for unobstructed beach, natural, and artificial vegetation. The blue line represents the unobstructed flow over the beach surface as recorded from M1, the red line represents the artificial vegetation and the yellow line is the natural vegetation. Both the natural and artificial vegetation wind speeds are recorded leeward of the vegetation from M2 and M3 as demonstrated in the arrangement in Figure 3.7b.

exponentially with increasing height above the bed. The anemometers at heights 0.5 and 0.9 meters above the bed show almost no variation in wind speed in comparison to the unobstructed anemometer. Only the anemometer located at 0.25 meters above the bed shows a slight influence of flow reduction from the frictional forces along the bed. This is like due to the height of the artificial vegetation as well as the uniform nature of the plants.

4.1.2 Natural Vegetation

Overall, it can be seen from the diagram in Figure 4.2 that the natural vegetation does not reduce flow velocity at the bed as efficiently as demonstrated by the artificial vegetation, although the percentage of velocity is similar at 70% for both types of vegetation. Similar to the artificial vegetation, the greatest deceleration of flow occurs between the 30% and 40% vegetation cover and also between the 40% and 50% vegetation cover. This indicates a similarity in the overall flow trends between the natural and artificial vegetation.

At lower densities, both the natural and artificial vegetation follow the same general pattern of deceleration near the bed with the artificial vegetation having the greatest deceleration near the bed. However, when examining the pattern of the wind speed profile for the natural vegetation at 30 percent density, there is a change in the general profile and there appears to be a reduction in wind speed higher up in the profile compared to the artificial vegetation. With increasing percent cover, the velocity slows until it reaches a point near the canopy surface and the flow reverses, indicating the wind speed is again increasing with height above the bed. Similar results are expressed in a study conducted by Hesp (1983). Although the trend represented here in the natural vegetation is not as clearly demarcated as the flow reversal demonstrated in the Hesp

(1983) study, the same general trend can be noted. The influence on wind speed higher in the boundary flow possibly indicates that the natural vegetation has a greater ability to extract momentum from oncoming wind compared to the profiles demonstrated by the artificial vegetation. A more in-depth comparison of flow, particularly the momentum flux between the two types of vegetation will be discussed further in Chapter Six.

It is also likely that the difference in the shape of the velocity profiles is a reflection of the overall difference in plant heights between the two vegetation types. It may also be a function of the variable plant heights within the natural vegetation in comparison to the uniform plant heights of the artificial vegetation. It must be taken into consideration that the natural vegetation is taller than the artificial vegetation. The natural vegetation has a mean height of 33 centimeters whereas the artificial vegetation has a mean height of 14 centimeters. This is most likely the cause of the reduction of wind speed higher up in the boundary layer in the natural vegetation.

The differences expressed here in the wind speed profiles are a result of the different morphologies between the natural and artificial plant types. This indicates that a direct comparison of vegetation with quite different morphologies is not an effective method to determining the relative changes in incremental vegetation densities. This is not to say that the experiment at present is not valid, however, the transition of the velocity profiles as demonstrated here not only reflect the changes in wind velocity with increasing plant density, but also the modification of wind speed in relation to different plant morphologies.

CHAPTER 5: REGRESSION ANALYSIS OF WIND SPEED VARIABILITY BETWEEN UPPER ANEMOMETERS

This chapter outlines the process used to simplify all wind speed data in order to determine the variability between anemometers placed at 0.9 and 0.5 meter heights above the bed for all masts. The purpose of this simplification was to reduce the boundary layer region used for momentum and sediment flux calculations. This was done by conducting a regression analysis between the unobstructed mast (M1) and the mast in the lee of the vegetation (M3).

5.1 Regression Analysis of Wind Speed Variability

A regression analysis between masts M1 and M3 was conducted for the anemometers situated at 90 centimeters and 50 centimeters above the bed for all artificial vegetation runs and all natural vegetation runs. Four regressions were completed in total, one for both natural and artificial vegetation at 90 centimeters above the surface, and another for both natural and artificial vegetation at 50 centimeters above the surface. This was conducted to analyze any variation in wind flow from the output of the upper most anemometers in the boundary flow. The output charts for comparison between the M1 and M3 velocities upon which all four regression analyses are based, are presented in Figure 5.1.

The results of the regression for artificial vegetation at the 90-centimeter height revealed a variation in wind speeds of 0.029m/s with an R^2 value of 0.97. This slight variation in wind speed is well within the boundaries of simple measurement error. Similarly, wind speeds recorded at 50 centimeters above the bed were also compared between M1 and M3 for the artificial vegetation runs. A regression between the two anemometers at this height for all completed runs gave an R^2 value of 0.987. However,

the intercept was 0.493 suggesting that there was a difference in wind speed of roughly 0.5 m/s between the two masts. Further analysis was completed regarding the difference in wind speed. Looking at the absolute difference between M1 and M3 showed there was a variation of wind velocity of only 0.09 m/s. A regression between the absolute difference and M3 indicates that there are two major outliers at the faster wind speeds that are responsible for 20% of this variability. Although it is a crude representation of flow, it is assumed that variability between anemometers at this height is still correlated closely enough to assume a relatively uniform wind speed. For this reason, only the flow recorded 50 centimeters below the bed will be analyzed for momentum extraction with increasing vegetation density.

Regression analysis for the natural vegetation at the 90-centimeter height anemometer also indicated some variability within the lower density runs as can be seen in Figure 5.1. With an R^2 value of .937, the variability in wind speed between M1 and M3 was found to be 0.14 m/s. This variation can be attributed to several outliers occurring during the lowest density runs. Although slightly high, for the purpose of this study, this value is considered to be small enough to assume that the difference between the anemometers is likely attributed to some equipment error. The results of each regression and all line-fit plots and residual plots for this and each of the four regressions can be found in Appendix C.

Assessing the regression analysis conducted between M1 and M3 anemometers set at 50-centimeter heights yields a regression of 0.985 and a variation of wind speed between the two anemometers of 0.019m/s. Similarly to the aforementioned regression analysis, this variation was considered to be well in the means of unavoidable

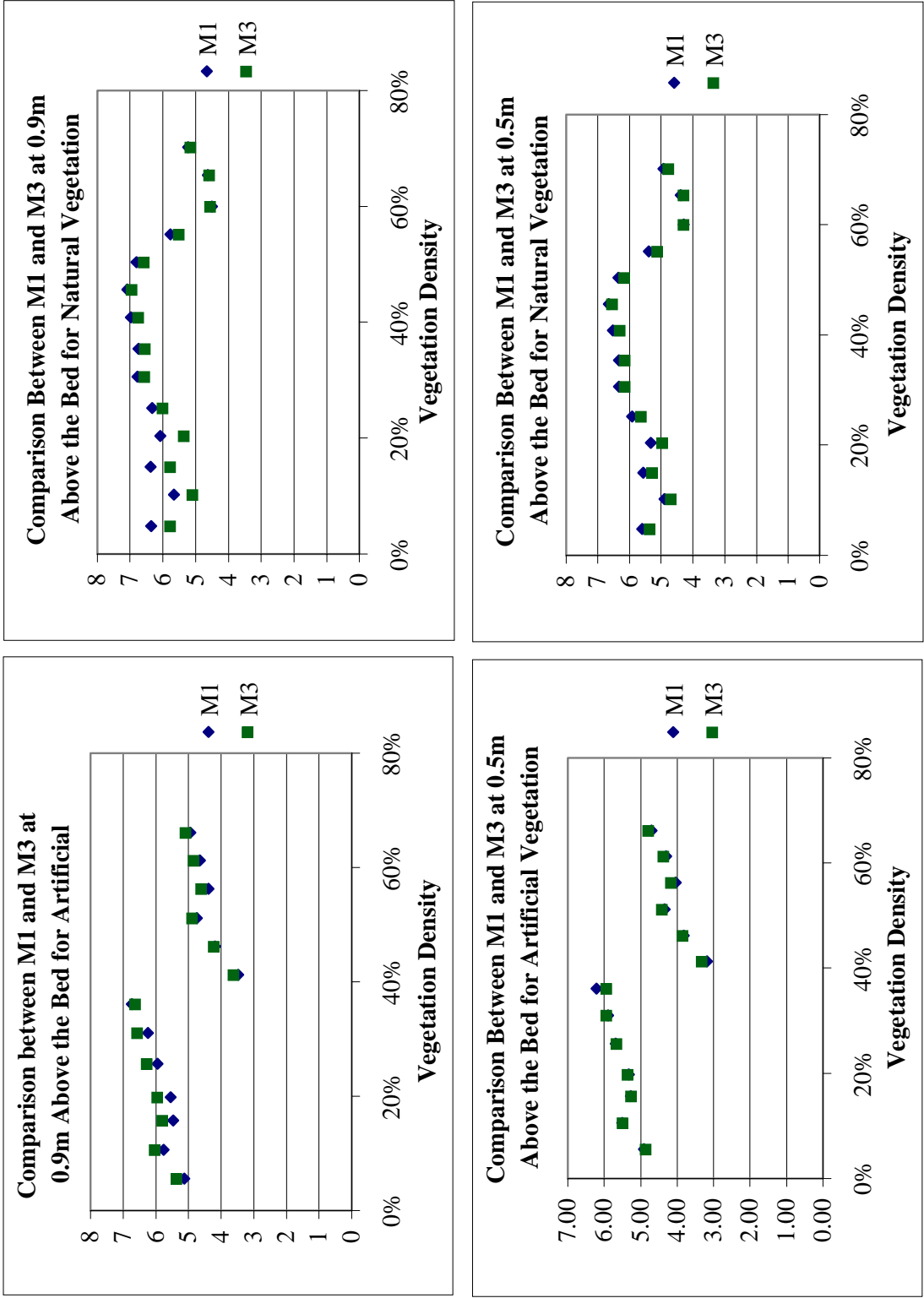


Figure 5.1: Comparisons of anemometer velocities for all run for both artificial and natural vegetation. The data presented here was used for all regression analyses.

measurement error. Assessment of each of the velocity profiles as shown in Figure 5.2 for all runs completed for natural and artificial vegetation also illustrates this point. It should be noted that Figure 5.2 illustrates only the lateral cover comparisons; however, the analyses were conducted using all data. Therefore, from the regression analysis output and visual agreement with the velocity profiles which both indicate a lack of variability in the uppermost portion of the boundary layer, the upper portion of the velocity profile is excluded from the momentum flux analysis.

5.2 Regression Output

The results of the regression indicate no significant variation between the two uppermost anemometers, located at 0.9 and 0.5 meters above the bed, for all three anemometer towers. Although there is a slight variation in wind speed in the upper boundary for the natural vegetation runs at lower densities, the regression indicates that the difference between the control anemometer mast and leeward mast is negligible and is therefore assumed to be equal. From this, only the bottom three anemometers from M2 and M3, and bottom two anemometers from M1, were utilized for momentum and sediment flux computations.

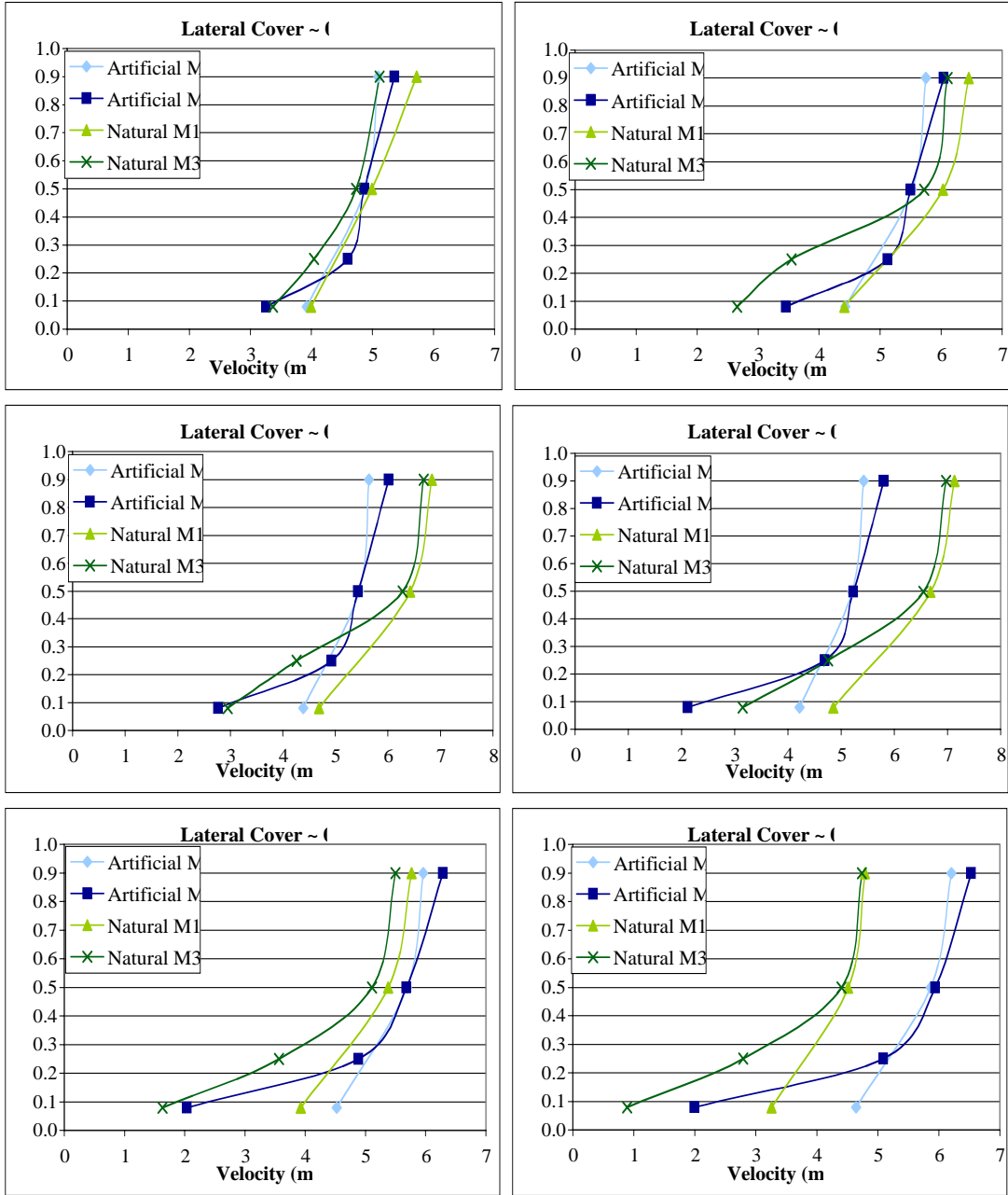


Figure 5.2: Velocity profiles for unobstructed tower (M1) and leeward tower (M3) for both natural and artificial vegetation. Natural and artificial vegetation regression analyses were completed independently and are only plotted together here for visual representation.

CHAPTER 6: MOMENTUM AND SEDIMENT FLUX VARIABILITY BETWEEN NATURAL AND ARTIFICIAL VEGETATION

Momentum flux represents the production of turbulence as it relates to the overall reduction of kinetic energy of wind flow over a given area. Because wind energy is required to transport sediment, a large momentum flux indicates that a large portion of the winds energy is removed from the flow and the wind is therefore unable to transport sediment further downwind. Therefore, by determining the potential momentum flux for a specific density, a generalization of sediment trapping efficiency may be made. Also, momentum flux calculations are used to determine how a plant can reduce soil erosion and reduce ambient dust particulates (Wyatt and Nickling, 1997; Gillies, *et al.* 2000). In terms of turbulence, momentum flux may also be represented by the Reynolds Stress, which may be expressed as:

$$\tau_R = \rho \sqrt{\overline{u'w'^2} + \overline{v'w'^2}} . \quad (17)$$

In this case however, only the horizontal and vertical shifts in wind velocity were available so a different method of deriving momentum flux was required.

Examining the potential momentum flux of natural and artificial vegetation rather than using solid elements as proxy indicators is important because the structure of natural vegetation has a greater ability to increase the rate of momentum flux over solid elements (Gillies, *et al.*, 2002). This may be attributed to the porous morphology of the plant, which in turn, increases the exposed frictional surface area capable of reducing wind speeds; and the flexibility of the plant. Fluttering leaves and waving branches provide another mode of energy dissipation. Here, we can examine how the momentum flux rate for natural and artificial vegetation as well as how the two compare.

6.1 Momentum Flux

Momentum flux was determined using a method similar to the method used to determine Reynolds Stress where both horizontal, vertical and directional vectors were included in the analysis simultaneously. A similar methodology has been used by Leenders, *et al.* (2005). By including both the horizontal and vertical vectors of the vegetated study site, it is possible to determine total momentum extraction over the entire study site rather than just the vertical reduction of velocity, which may be illustrated by a simple velocity profile. The following diagrams in Figure 6.1 illustrate the momentum flux calculations for both the natural and artificial vegetation. Momentum flux is plotted against the corresponding lateral cover (L_C) as it was computed earlier in Figure 6.1a, and against volumetric percent cover in Figure 6.1b.

Undulations in the graphs representing both lateral and volumetric percent cover are purely a result of natural fluctuations in wind speed over the beach. Two high peaks are evident in both the artificial and natural vegetation graphs representing volumetric percent cover (Figure 6.1b). These peaks for artificial and natural vegetation in Figure 6.1b correspond to the highest velocities recorded throughout the study for both vegetation types. Had these two vegetation types been recorded simultaneously, it is likely that these peaks would have lined up on the graph. Due to the method of calculating momentum flux applied here, these values reflect the absolute difference in the increased wind speed higher in the boundary flow, and the simultaneous flow reduction near the bed by the vegetation. From this it is important to note that both vegetation types increase the rate of momentum extraction from oncoming wind flow as wind velocity increases.

Upon assessment of the data organized to demonstrate lateral cover, the natural vegetation appears to extract more momentum from the flow in comparison to the artificial vegetation. However, addressing the momentum flux curves for both artificial and natural vegetation when plotted against volumetric percent cover suggests that the potential for momentum extraction between the artificial and natural vegetation is similar. This allows some room for interpretation.

6.1.1 Lateral Cover

Assessing the momentum extraction curves for lateral cover, it was first thought that the higher momentum flux demonstrated by the natural vegetation was purely a function of the differences in height between the two types of vegetation. It seems logical that natural vegetation would have a greater potential to extract momentum from oncoming wind flow because it extended higher up into the boundary layer flow and is more flexible. The method used to calculate momentum flux uses both horizontal and vertical vectors to calculate the change in momentum. Because the horizontal component (which is represented by the length between M1 and M3), is consistent for all runs, it becomes factored out, leaving only the difference in the vertical components, which is the difference in heights between the two types of the vegetation.

Plotting a trend line through the natural and artificial momentum flux data points provides a generalized idea of how each vegetation type extracts momentum with increasing density. Assessing the slopes of the trend lines for the natural and artificial vegetation, it can be seen that both are similar with artificial vegetation having a slope of 0.76 and natural vegetation having a slope of 0.87. This trend indicates that although the natural vegetation extracts more momentum in comparison to the artificial vegetation, the rate of extraction between the two vegetation types is similar as vegetation density

increases. As the data was reduced, there is a decrease in the points of density cover examined and with higher density covers, this trend may or may not continue. Although the natural vegetation is somewhat higher, it is possible that this difference is a factor of instrument error or slight calculation errors in determining the area under each of the log profiles.

From the data presented here, it may be seen that there is negligible difference between the potential momentum flux between the natural and artificial vegetation with natural vegetation having only a slightly greater potential to extract momentum. More research is necessary to determine a more solid conclusion in regard to the comparison between natural and artificial vegetation. Also, a larger range of lateral cover densities is required for further analysis. From the results here, it can be seen that the lateral cover ranges do not reach percent covers dense enough to produce skimming flow according to Wolfe and Nickling (1996).

6.1.2 Volumetric Density

Examining the momentum flux curves plotted against volumetric percent cover illustrates a different picture than the one demonstrated by the lateral cover curves (Figure 6.1b). In the graph concerning the volumetric percent cover, it appears that there is less of a difference in the potential for momentum extraction between the two vegetation types and the vegetation data are closer together in regards to potential momentum extraction. The natural vegetation still shows a greater potential for momentum extraction compared to the artificial vegetation however, the gap between the two is minimized and the artificial vegetation surpasses the momentum flux of the natural vegetation at roughly 60% density cover. The values expressed by both vegetation types are also lower in comparison to the lateral cover graph.

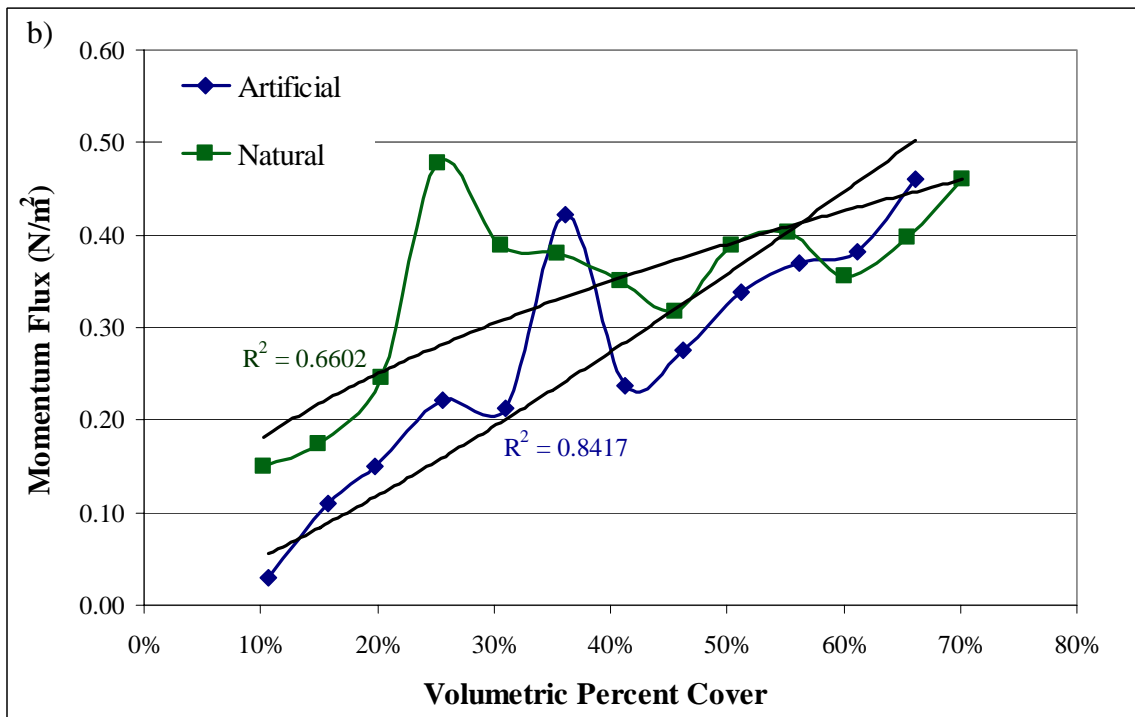
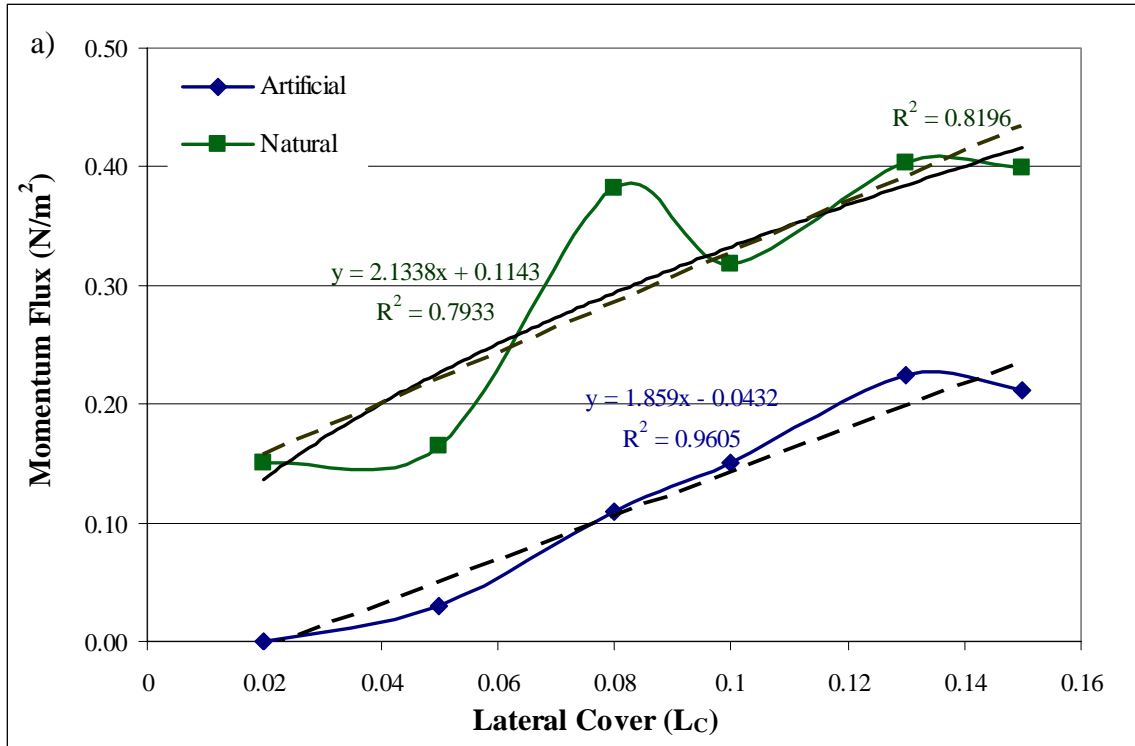


Figure 6.1: Momentum flux calculations with increasing vegetation cover as demonstrated by a) lateral cover and b) volumetric percent cover. The solid lines represent a power function. The dashed line represents a linear trend line for the purpose of comparing slope.

Plotting a linear trend line through each of the vegetation types gives a slope of 0.839 for the artificial vegetation and a slope of 0.563 for the natural vegetation. These slopes are much lower in contrast to the slopes presented in the lateral cover graph. The slopes of the trend lines also indicate that the artificial vegetation has a higher rate of momentum extraction in comparison to the natural vegetation and has the potential to exceed the momentum flux of the natural vegetation at higher densities. However, the position of the lines relative to each other is in agreement with the lateral cover graph, indicating that natural vegetation has greater potential for momentum extraction. There are several components here that are most likely responsible for the variation between the lateral cover and the volumetric percent cover graphs.

One of the differences in the flow patterns between the two different types of vegetation may be the manner in which they have been reduced into lateral cover and volumetric percent cover categories. From the values presented by Wolfe and Nickling (1996) and also presented in Table 7.2, it can be seen in the lateral cover graph that none of the densities plotted are high enough to reach skimming flow, and only reach roughly the mid-range of wake interference flow. Therefore, the potential rate of momentum extraction should be similar. However, in the volumetric percent cover plot, the slope of each line shows a very different rate of momentum extraction for both vegetation types.

As discussed in the literature review, lateral cover represents an oversimplification of the three-dimensional morphology of the plant form. However, it will be demonstrated in Chapter Seven that far more artificial plants were placed on the pegboards in comparison to natural vegetation as a result of their differences in volume. As a result of having more artificial plants present on the pegboard compared to natural plants, it is highly likely that the artificial vegetation reached skimming flow far before

the natural vegetation plot. From the spacing between the natural plants, even at the higher densities, is it questionable as to whether skimming flow was reached at all. This is most likely the reason artificial vegetation has a greater overall slope in the volumetric percent cover. Because skimming flow actually shifts the whole boundary layer profile upwards, increasing the height of Z_0 , reaching skimming flow in one type of vegetation and not the other, will offset the momentum flux for the purposes of comparison. It is most likely that this trend was not observed in the lateral cover plot because the density range is too low for skimming flow to occur. It is highly likely that with a greater range of lateral cover densities, a similar trend would occur with artificial vegetation reaching skimming flow before the natural vegetation.

From this, it may be deduced that both methods of assessing percentage cover of vegetation are useful but not without their shortcomings. Lateral cover demonstrates that both artificial and natural vegetation have the same rate of momentum extraction; however, the natural vegetation's potential for momentum extraction may be overestimated as a result of the simplified manner in which lateral cover is determined. The volumetric percent cover approach is not without fault either. It does illustrate that the momentum extraction between the two vegetation types are more equal, however, it cannot account for the transition into skimming flow by one type of vegetation before the other. This being said, it is likely that the lateral cover method also lacks this capability and would thus be unable to compensate for variable transitions of flow between vegetation types.

In terms of model development, if momentum flux values are required, it is unlikely that either of these methods would greatly benefit over the other. In other words, neither approach is ideal in that both methods have advantages and disadvantages

over the other. For the purposes of evaluating momentum flux in the field, it may be easier to quantify lateral cover, however, the short-comings of its application as they are presented here should be kept in mind as an over or underestimation of the potential for momentum extraction is highly possible.

6.2 Sediment Flux

Potential sediment flux estimations were determined using a model developed by Lancaster and Baas (1998). This was not done to compare, prove, nor disprove the application of this model. This model was selected primarily for its ease of use and because the variables required do not readily depend on constants or unknown values that must be assumed to be applicable to this study site. In the same manner as the momentum flux calculations, estimated sediment flux values were calculated for both the lateral cover data and the volumetric percent cover data. The resulting graphs are demonstrated in Figure 6.2 where Figure 6.2a shows predicted sediment flux using lateral cover and Figure 6.2b illustrates predicted sediment flux using volumetric percent cover. It should be noted that the sediment flux value for 25% cover for natural and 36% cover for artificial data points were removed from the sediment flux graph illustrated in 6.2b. Both of these points were outliers and their removal did nothing to offset the general trend of the data set.

6.2.1 Comparison Between Lateral Cover and Volumetric Percent Cover

Several interesting results come to light upon examination of these two graphs presented in Figure 6.2. The first point of interest is that there are no differences between the lateral cover method and the volumetric density methodology for the projected rate of sediment flux for either type of vegetation. It must be noted that the range of lateral cover is smaller than the range of percent cover; however, the artificial data as

represented by lateral cover directly corresponds to the portion of volumetric density between the 10% and 30% cover range. This should be expected as both the range of percent cover, lateral cover and flow type all correspond to the guidelines presented by Wolfe and Nickling (1996).

It may also be noted that the trend demonstrated by natural vegetation in the lateral cover graph is similar to the overall trend natural vegetation demonstrates in the volumetric percent cover graph. In all cases, the results are in agreement with work conducted by Fryrear (1985), Leys (1991) and Lancaster and Baas (1998), which demonstrate an exponential decrease in sediment flux with increasing vegetation density. In the volumetric percent cover graph, the natural vegetation shows a strong decrease in sediment flux with a small increase in percent cover, but then quickly stagnates around 30% cover. From this point there is little change in sediment flux with continued increase in percent cover. This is most likely a reflection of the problem of comparing two different plant morphologies as will be discussed further in Chapter Seven. In addition, not enough natural plants were added to the study site to determine a more accurate representation of percent cover. This reinforces the problematic nature of attempting to directly compare two different types of vegetation with different plant morphologies. From the results shown, it is highly probable that the actual percent cover for natural vegetation is far less than calculated. This is also seen in Appendix B where it is illustrated how the lateral cover comparisons were defined.

6.2.2 Sediment Flux and Its Applications

Although it has been stated that it is very likely that the actual percent covers for natural vegetation are lower than have been estimated here, the potential rate for sediment flux for the natural vegetation is much higher than for artificial vegetation for the same

percent cover and lateral cover. This suggests that natural vegetation is highly efficient at reducing sediment movement and may even be more efficient than expressed here due to the likely overestimation of percent cover. In Figure 6.3, the same graphs presented in Figure 6.2 are plotted with a line added to allow for the comparison of the percentage of flow reduction between natural and artificial vegetation.

Both the lateral cover and volumetric percent cover graphs illustrate that the natural vegetation is more efficient at reducing sediment flux. The trend line for each is used to delineate the predicted sediment flux rate for each percent cover and lateral cover. The trend lines offer a more suitable representation of predicted sediment flux and smooths the undulations as seen in the raw data. A 90% reduction in sediment flux occurs at a lateral cover of roughly 0.05 lateral cover for the natural vegetation. Addressing the volumetric percent covers, the natural vegetation reduces sediment flux by 90% at roughly 30% cover. In other words, in order to reach a 90% reduction in sediment movement as it has been predicted here, a minimum of 50 plants should be planted for an area equal to 1.22m^2 . Although the vegetation used in this study is more similar to vegetation used in the study conducted by Kuriyama, *et al.*, (2005), the results presented here are in closer agreement with those demonstrated by Lancaster and Baas (1998) who report a 90% decrease in sediment flux at roughly 12% vegetation cover. A further reduction of 95% sediment flux can also be seen at 42% cover for natural vegetation showing that natural vegetation has a high potential for reducing sediment transport with very few additional plants for a specified ground coverage area. This is roughly equal to planting 67 plants for an area of 1.22m^2 . In contrast, the artificial vegetation has the potential to reduce sediment flux by 90% at roughly 44% vegetation

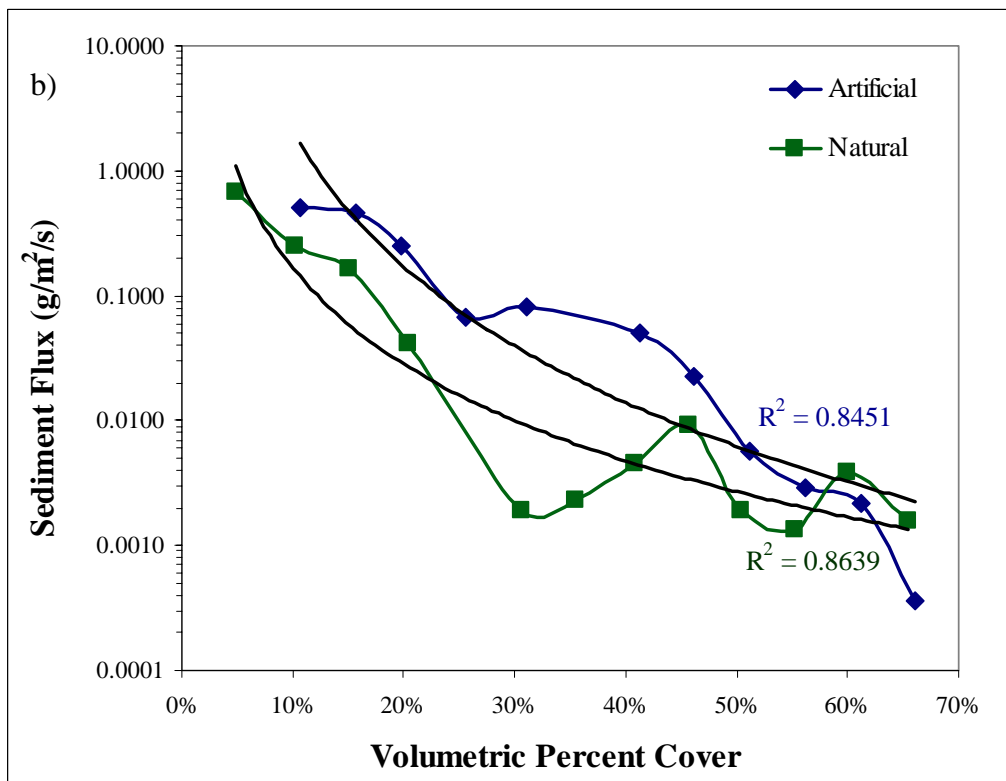
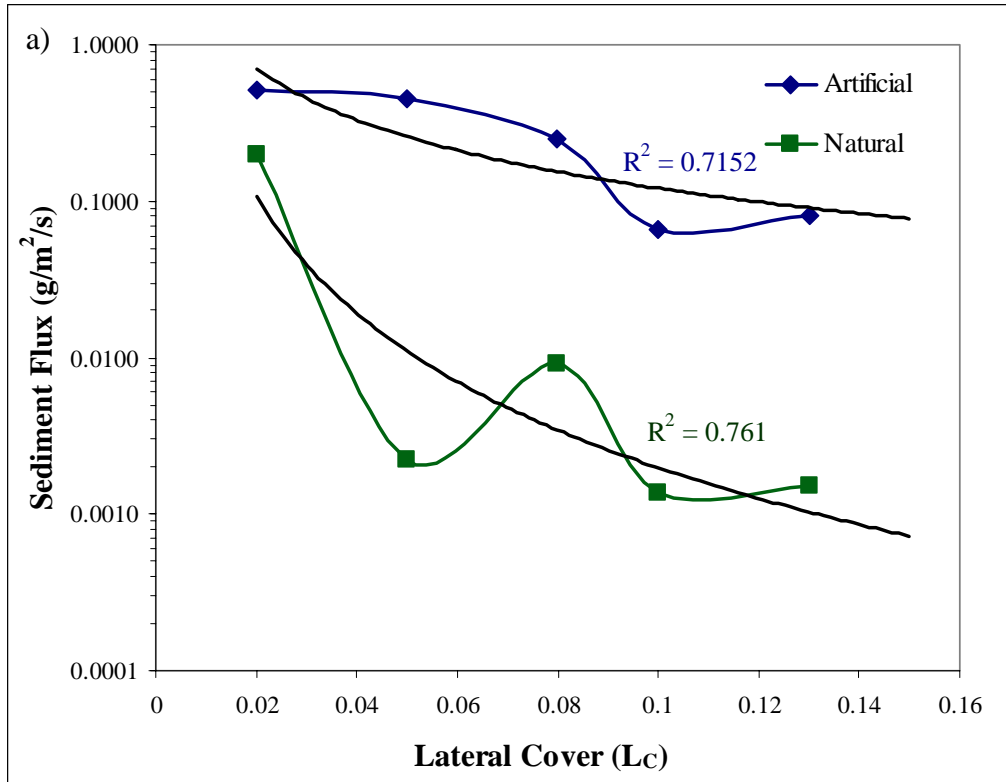


Figure 6.2: Estimated potential sediment flux in relation to a) lateral cover and b) volumetric percent cover.

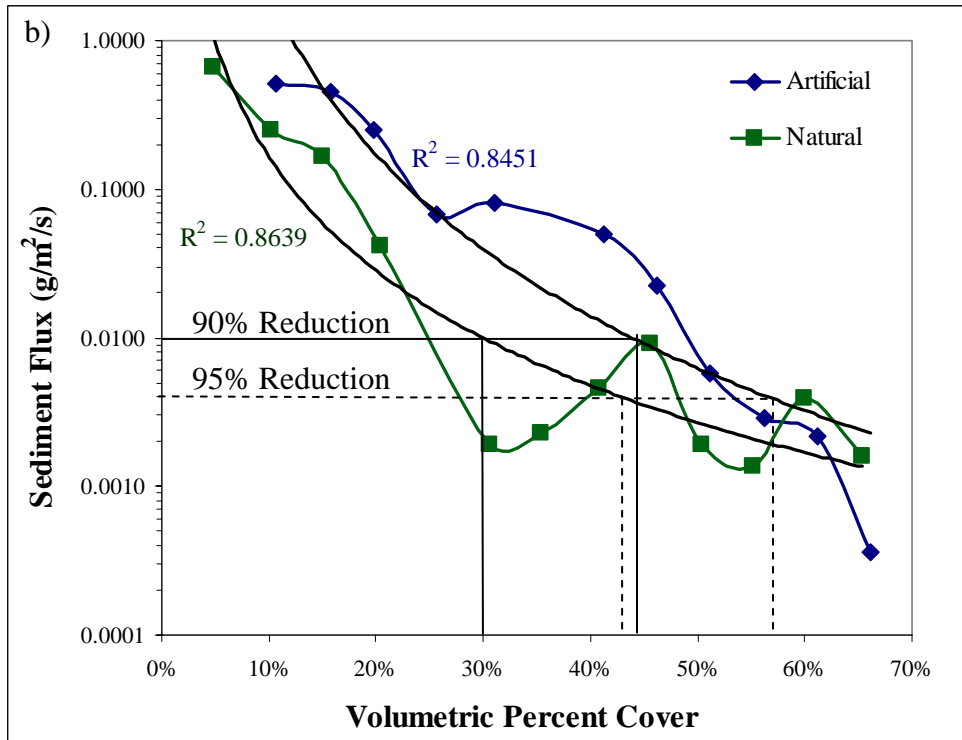
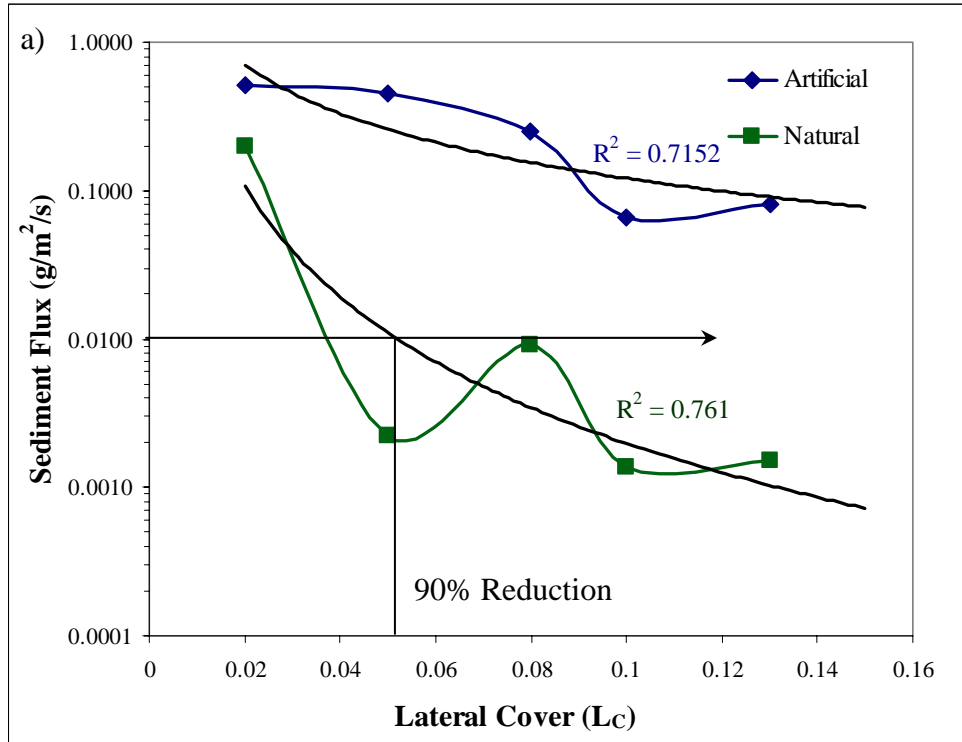


Figure 6.3: 90% and 95% reduction in estimated potential sediment flux for both a) lateral cover and b) percent vegetation cover. Here, the amount of artificial and natural vegetation required to reduce sediment movement by a certain percentage is illustrated.

cover, however, it does not reduce sediment flux by 95% until roughly 58% vegetation cover. With increasing percent cover, artificial vegetation appears to continue to reduce sediment flux reaching a 99% reduction of sediment flux at 50% vegetation cover. This is consistent with Wasson and Nanninga (1986) where it was demonstrated that it is still possible to have sediment movement at 45% cover.

CHAPTER 7: VOLUMETRIC DENSITY AND LATERAL COVER COMPARISONS BETWEEN NATURAL AND ARTIFICIAL VEGETATION

This chapter will examine the methods used to determine vegetation cover by means of calculating the volume of the roughness elements. Here, we examine the visual relationship of natural and artificial vegetation plots which, in terms of volumetric percent cover, were calculated as having equal plant densities. This leads to an examination of the relationship between the surface area and the volume of the same plant individual, and how the two measures relate to each other. This chapter will also compare how this new volumetric density method relates to the lateral cover method, a method that has been applied to previous studies.

7.1 Background

When this study was initiated, it was considered that plant ‘density’ may be more adequately measured by calculating the volume, or three-dimensional ‘area’ of each plant. Using the volume of a plant to determine its density cover seemed plausible because the volume of a plant remains constant despite changes in wind velocity or wind direction. This cannot be said for the lateral cover method, which can only account for a frontal representation of a plant. If wind speed changes and the vegetation bends into the wind flow, the lateral cover will change accordingly, as discussed in Chapter 2. Thus, the study was carried out with this in mind. When only the artificial vegetation type was examined, this approach seemed reasonable. However, when natural plants were introduced, it became apparent that this method of density calculation may be flawed. The following outlines how the density calculations seem flawed and what procedures were completed in order to allow for a reasonable comparison between the natural and artificial plant types.

7.2 Volume Calculations for Artificial and Natural Vegetation

The volume of an individual artificial plant and natural plant was calculated following the procedure outlined in Chapter 3.2.1.i. Volume calculations between artificial and natural vegetation varied drastically. The average volume of an artificial plant was 24.28cm^3 whereas a natural plant had an average volume of 87.76 cm^3 . These values were used to determine the percentage cover of a single plant for the pegboards, which was subsequently used to determine how many plants of each vegetation type were required to reach a specific density. Figure 7.1 is a collection of these images ranging from lowest percent cover (10 percent) to highest percentage cover (60 percent). Comparing the images of percent cover directly, it can be seen that there is a large difference in the density between the two types of vegetation.

From these images it becomes visually clear that the densities between the two vegetation types are not equal relative to each other. The percent cover of artificial vegetation appears to have a higher density in comparison to the natural vegetation when in fact, they are supposed to be equal to each other. This raises questions regarding the methodological approach to the problem of formulating a percent cover using volume over a flat surface area. It seems logical to use a three-dimensional approach to quantify percentage cover of vegetation because the vegetation is three-dimensional in form. However, upon further reflection of the methodology applied here, the outcome is flawed in that it was calculated by dividing a three dimensional shape over a two-dimensional surface area. With such complications and time consuming measures involved in volumetric calculations, it becomes clear why researchers continue to follow or modify the original two-dimensional method of calculating lateral cover (McDonald, *et al.*,1998).



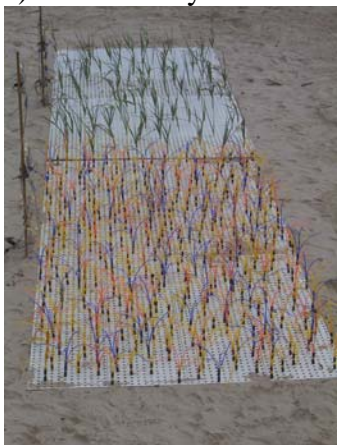
a) 10% Density Cover



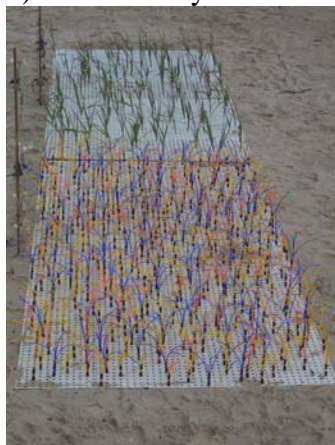
b) 15% Density Cover



c) 20% Density Cover



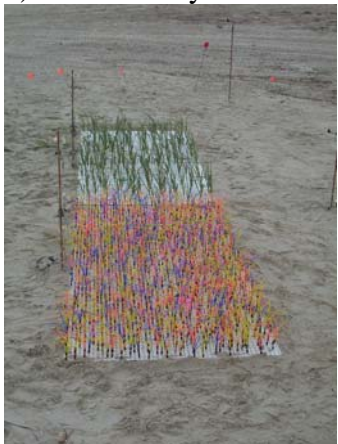
d) 25% Density Cover



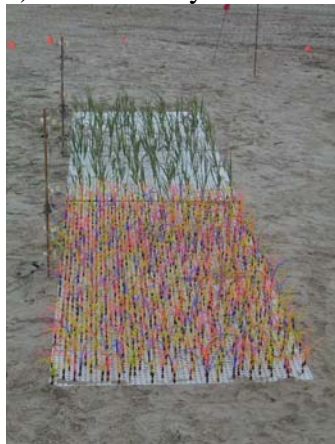
e) 30% Density Cover



f) 40% Density Cover



g) 50% Density Cover



h) 60% Density Cover

Figure 7.1: Incremental increases of equal density for both natural and artificial vegetation for direct comparison. These densities were plotted according to the calculations determined by the volume of each of the two types of vegetation. Artificial vegetation is the multi-coloured stems and is always in the foreground of the images. The natural vegetation is situated in the background.

7.3 Relating Surface Area and Volume of a Single Plant Individual

Addressing the problems with determining the volume of each plant raises the question as to whether or not it would be more suitable to use the total surface area of each plant individual rather than its volume, simply for ease of calculation. This is not to be confused with older methods whereby plant density was determined by taking a visual estimate of the ground surface area covered by vegetation. The important aspect of determining the surface area of an individual plant is that it will also remain constant, like plant volume, despite changes in wind flow patterns. Figure 7.2 shows the relationship between the volume and surface area calculations for natural vegetation. No regression between surface area and volume of artificial vegetation can be plotted because each of the plant individuals is uniform in shape. Natural vegetation has the most variability between each individual but there is still a high correlation between the volume calculation and the surface area calculations for the same plant individual with an R^2 value of 0.9167. The slope of the line also indicates a close relationship between the two parameters, which is in close approximation to a one to one relationship. This suggests that determining an average surface area of plant individuals may serve as a proxy for volume as it far less labour intensive to measure.

It is clear that the strong link between the volume and surface area of the natural vegetation is directly related to the large leaf surface on each plant individual. The 'leaves' of the artificial vegetation in contrast, are very thin relative to their length and add very little surface area or volume to the total volume and surface area calculations. Comparatively, the leaves of the natural vegetation used in this study are wide and elongated. They are often almost as long as the total height of the plant stem and wider. Having three to four of these larger leaves greatly increases both the surface area and the

volume of the plants. It is only logical to assume that the volume of the stem of the plant would be greater than its surface area, thus leaving the leaves to account for the close relationship between the surface area and volume calculations of a plant individual. Thus from this analysis, it is shown that there was very little difference between the surface area calculations and the volumetric calculations that were applied in the field.

Therefore, using surface area to calculate the density cover of the vegetation would have rendered similar results.

From this, it may be deduced that the artificial and natural vegetation densities cannot be directly compared due to their difference in morphology (different leaf shapes and lengths). Due to the volume ratio between the artificial and natural vegetation, which is close to a one to four relationship, compensating by increasing the number of artificial plants due to their smaller volume apparently does not visually appear to create an equal percent cover over the pegboards. This exemplifies the problems and complexities that arise when two totally different shapes are examined and compared. This is not to say that this methodology is not relevant, however, it may only apply to studies where only a single species is examined rather than as a comparison between different types of vegetation.

7.4 Comparison of Calculated Volumetric Density and Lateral Cover Calculations

Lateral cover values were computed for all recorded plant densities, including runs where natural and artificial vegetation were plotted independently from the other using the method demonstrated in Figure 3.7a. Lateral cover computations are based on the volumetric density calculations as they were determined in the field.. This ensures that the same number of plant individuals is represented for both calculations. A table demonstrating this process and the final results can be found in the Appendix A.

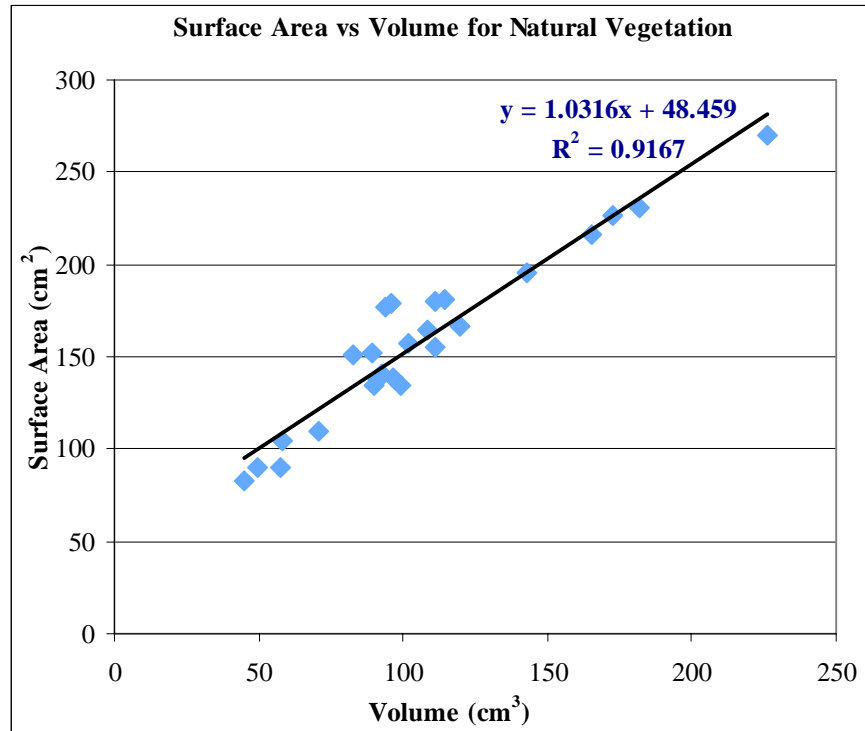


Figure 7.2: Direct comparison between surface area calculations and volume calculations for natural vegetation plant individuals.

7.4.1 Relationship Between Lateral Cover and Artificial Vegetation

Plotting the variability between the each of the three roughness elements provides a better idea of how each of the three roughness elements vary in regards to their specific volumetric and lateral cover calculations. Figure 7.3 shows this relationship, depicting each roughness element individual in relation to the associated lateral and volumetric density calculations.

The important point to draw out from Figure 7.3 is the relationship of the slope between each of the lines. It can be seen here that there is a one to one relationship between the lateral cover and the method used to calculate density for the dowels. This may be expected because there is no variation in the dowel's form meaning that there is no portion of the shape that could be excluded in a frontal parameterization of the object (e.g. leaves). This may explain the slope gradient for the natural and the artificial plants,

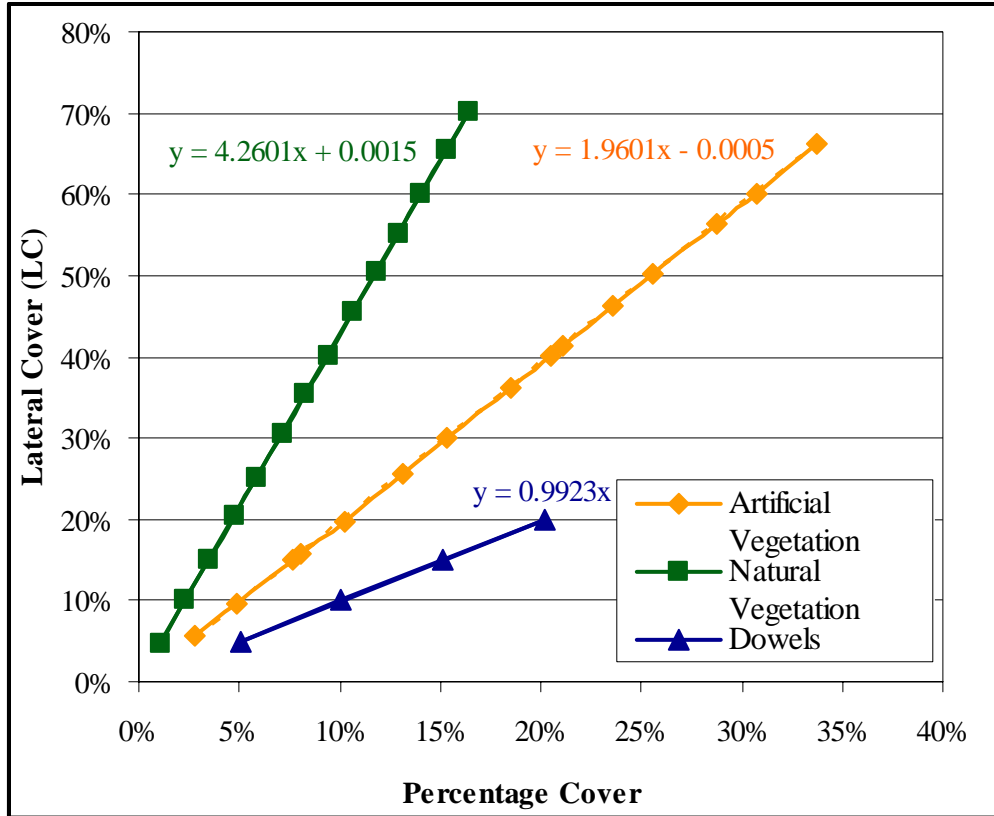


Figure 7.3: Comparison between the lateral cover calculations and the volumetric percent cover. The top line represents the dowels, the middle line is the artificial vegetation and the bottom line represents the natural vegetation.

which demonstrate a one to four relationship and a one to two slope relationship respectively. Evaluating the variability in the morphology between each of the three types of roughness elements, it may be said that the divergence away from a standard geometric shape accounts for the differences in volumetric density cover and lateral cover calculations. It is most likely that this variation between each of the three roughness elements is a function of the variation in shape and dimensions.

The differences in slope shown in Figure 7.3 indicate two points: the first is that using solid elements to represent natural vegetation is misleading and will most likely lead to a significant underestimation of the total coverage of an area covered by natural vegetation. Second, comparison of the slope of each line shows that even if the

volumetric calculations are a poor measure of vegetation cover, the variation in lateral cover alone indicates a large overestimation of lateral cover between the solid and natural elements. This would suggest that models that have been developed to examine flow dynamics over roughness arrays constructed of solid elements which are intended as a proxy for natural vegetation, may not be anywhere near as accurate as previously suggested.

Since solid elements may not be an accurate substitute for natural vegetation, artificial vegetation may provide a better middle-ground representation. The slope of the line reflecting artificial vegetation falls directly between the solid elements and the natural vegetation. This suggests that, although it is not a perfect representation of natural vegetation, artificial vegetation provides a closer representation of natural vegetation's shape than solid elements. Because working with natural vegetation can be extremely difficult and labour intensive, using artificial vegetation to substitute for natural vegetation is likely to produce more accurate results for model building compared to solid elements.

Although more work on the subject of comparing new approaches to determining a more accurate measure of vegetation cover must be considered, the results demonstrated here in this basic study suggests that previously used methods may be inaccurate. This also indicates that previous studies that have relied on the parameterization of lateral cover or roughness density to determine rates of sediment deposition may yield inaccurate results.

7.4.2 Comparison of Values to Previous Studies

Table 7.1 shows a comparison of the plant volumes percentage cover and the corresponding lateral cover calculations for each of the three roughness elements

examined in this study. Each of the corresponding calculations was made with all variables being equal, including number of plants and pegboard size. All variability between volumetric and lateral cover computations is a direct function of the methods used to derive each parameter. What is important to note from Table 7.1 is the variability between volumetric and lateral cover calculations as well as the variation between the vegetation types for the same density measures. Table 7.2 shows the traditional values for comparison between lateral cover and percent cover.

Table 7.1 can be compared to Table 7.2, which has been modified from Nickling and Wolfe (1996). Comparing the values in Table 7.1, it becomes clear that the artificial vegetation complies with the values stated in Table 7.2 closely and is almost an exact match. Natural vegetation calculated for this experiment however, is far lower than the values reported in Table 7.2 throughout all the percent covers reported. According to the values given in Table 7.2, the natural vegetation plots did not exceed roughly 40% vegetation cover. From here, it becomes difficult to determine whether calculating percent cover of vegetation using volumetric density is successful or not. The artificial vegetation seems to fit within the parameters of percentage cover outlined in earlier studies. However, the natural vegetation does not match the suggested lateral cover/percent cover amounts and appears to be greatly underestimated when calculated using the volumetric approach.

Table 7.1: Variation in volumetric density and lateral cover calculations for corresponding vegetation plots.

Artificial		Natural		Dowels	
Volumetric Density	Lateral Cover	Volumetric Density	Lateral Cover	Volumetric Density	Lateral Cover
5.55%	0.028	4.80%	0.011	5.00%	0.050
10.65%	0.054	10.20%	0.022	10.00%	0.101
15.00%	0.077	15.00%	0.035	15.00%	0.151
19.80%	0.103	20.40%	0.048	20.00%	0.202
25.65%	0.131	25.20%	0.059		
30.00%	0.153	30.60%	0.072		
36.15%	0.185	35.40%	0.083		
40.05%	0.205	40.05%	0.094		
46.20%	0.236	45.60%	0.107		
50.10%	0.256	50.40%	0.118		
56.25%	0.287	55.20%	0.129		
60.15%	0.307	60.00%	0.140		
66.15%	0.338	65.40%	0.153		
		70.20%	0.164		

Table 7.2: Roughness element descriptions. Modified from Wolfe and Nickling (1996)

Roughness Element Descriptions		
Flow Regimes	Percent Cover (%)	Lateral Cover (L_c)
Isolated Roughness Flow	<16	< 0.082
Wake Interference Flow	16-40	0.083 – 0.198
Skimming Flow	>40	>0.198

CHAPTER 8: CONCLUSIONS

There are several conclusions that can be drawn from the data that has been presented here:

1) The flow characteristics of the natural vegetation follow the overall trend illustrated by Hesp (1983), where flow is reduced higher in the boundary layer and then accelerates over the canopy top. Overall, the artificial vegetation reduces flow velocity more efficiently near the bed with the highest reduction of wind speed occurring between 30% to 50% vegetation cover. Natural vegetation also shows the greatest deceleration of flow between 30% to 50% vegetation cover. This is in agreement with the literature and suggests that this percent cover range may be the most ideal for reducing wind velocity, a key component for sediment deposition and subsequent foredune development.

2) Natural vegetation with similar morphology to *Panicum amarum* (beach grass) demonstrates little variation between its calculated surface area and volume. This can be attributed to the large, elongated leaves of the plant, which make up the greater part of its biomass. The long, flat leaves do little to add to the volume of the plant because they are very thin, thus the volume of the leaves themselves is roughly equal to the surface area. From this, it may be inferred that either the volume of the plant or total surface area may be used to define a three-dimensional representation of the plant relative to the area it occupies. For future studies, establishing the surface area of the vegetation may prove to be less labour intensive and less likely to incur fundamental measurement errors. Also, the morphology of different plant species can be highly variable. It is proposed that implementation of the volumetric or surface area percent cover approach should only be conducted comparatively by examining plant types with similar morphologies.

3) Although not perfect, the morphology of artificial vegetation provides a better roughness element than solid elements for the purpose of analyzing the mechanics of flow. Solid elements lack the flexibility and the porosity of natural vegetation; therefore, developing models that are designed for application to the natural environment but implement solid roughness elements, will likely provide misleading results. Artificial vegetation has the potential to act as a 'middle ground' tool for modeling purposes. As it is demonstrated in Chapter Seven, artificial vegetation may not be a perfect representation of natural plant morphology but it does have more a more appropriate representative morphology in comparison to a solid cylindrical roughness element. This being said, the relationship between natural and artificial vegetation in regards to sediment flux is likely a closer match in comparison to solid elements and the sediment flux rate associated with them. When applied for the purpose of modeling in a wind tunnel, it is more likely that the application of artificial vegetation will yield results that are more representative and applicable to the natural environment. In other words, if natural vegetation cannot be used during model development, using artificial vegetation rather than solid elements, is more likely to produce results that will be more reflective of momentum and sediment flux rates in a natural setting.

4) Despite the shortcoming of having fewer natural vegetation densities compared to the range of artificial plant densities that were examined, the momentum flux for natural vegetation is slightly higher than that of the artificial vegetation for the lateral cover and volumetric percent cover. The difference in potential amount of momentum extraction between the natural and artificial vegetation is likely a function of variation in plant morphology between the two vegetation types examined here. Compared to volumetric percent cover, lateral cover presents greater variability in regard

to potential momentum flux between the two plant types. The differences between these two plots is a function of two things; the inability of lateral cover to account for the three dimension form of both vegetation types, and the inclusion of lower natural vegetation densities as they are plotted in the volumetric percent cover graph.

5) Estimated potential sediment flux rates for both natural and artificial vegetation follow an exponential decrease in sediment flux with increasing vegetation cover, meaning that more sediment will be trapped within the vegetation with only a small increase in the number of plants per area. The natural vegetation shows a greater rate for potential sediment trapping, reducing predicted sediment flux by 90% in only 18% volumetric cover and the artificial vegetation requiring 25% volumetric cover. Both of these values fall within the range presented in the literature from previous field studies. This suggests that the artificial vegetation, although not without its fault, acts as a good proxy for natural vegetation for the purposes of modeling sediment transport.

The ideal planting density to promote foredune growth and development may be as low as low as 18% to reduce sediment flux by 90%. This is likely to be the extreme lower range limit of ideal planting densities for sediment trapping and is likely only to be suitable for lower wind speeds, however, if this minimum vegetation cover is attained, the data suggests that foredune development will occur. For application purposes, this suggests that a minimum of 50 natural plants should be planted within an area roughly equal to 1.22m^2 in order to reach a reduction of 90% of sediment movement as it has been predicted here. In order to reach a reduction of 95% predicted sediment movement, a total of 67 plants should be planted for an area of 1.22m^2 . For application purposes, it is suggested that the larger number of plants, 50 per m^2 , should be maintained for foredune restoration purposes.

8.1 Future Research

It is apparent from the research conducted for this project that more refinement of the process of determining the surface area or volumetric percent cover is necessary. Both these methods are somewhat time consuming and labour intensive. More research is necessary to determine the variability between this volumetric method of representing vegetation and the lateral cover method with a more solid representation of vegetation density. This would determine if there is any need to represent vegetation in a three-dimensional construct of the two-dimensional lateral cover method is adequate.

Also, a direct comparison of solid elements, artificial vegetation, and natural plants, at controlled densities would determine a more concise ratio of both momentum flux and potential sediment flux differentials between each of the three roughness elements. This would ground the argument that solid elements are inappropriate substitutes for natural vegetation.

Additional anemometers and masts would also serve to improve this project greatly. Implementing sonic anemometers within close proximity to the canopy would provide a better means of determining Reynolds Stress (τ_R) within and behind the vegetation. More anemometers, specifically closer to the bed would also provide a more complete representation of flow patterns below the canopy and how each incremental increase in vegetation density effected wind flow patterns.

The initial design of this project was to record sediment deposition within the different vegetation types for each density increment. Unfortunately, experimentation for this research took place during an incredibly active hurricane season and with the arrival of the storm surge by Hurricane Dennis, prospects of the beach drying out enough for sediment movement were significantly reduced. As a result, no accumulation of

sediment was measured as none occurred. It would be of great advantage to replicate this experiment with sediment trapping to test the accumulation models developed by Wasson and Nanninga (1986), Lancaster and Baas (1998) and Bagnold (1941) more thoroughly using controlled density arrays.

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APPENDIX A: LATERAL COVER CALCULATIONS

$$L_C = DA_S$$

Where: D = Canopy Population Density
 - (Number of individuals per unit area)
 Unit Area = 1.22m * 1.22m
 A_s = Frontal Silhouette
 S = Surface Area of plant

Artificial Vegetation

A_s = 0.00114 m²
Unit Area= 1.4884 m²
Surface Area (S)= 0.000879 m²

Volumetric Percent Cover	Number of Plant Individuals	Lateral Cover (L_c)
5.55%	37	0.03
9.60%	64	0.05
15.00%	100	0.08
15.75%	105	0.08
19.80%	134	0.10
25.65%	171	0.13
30.00%	200	0.15
36.15%	241	0.18
40.05%	267	0.20
41.25%	275	0.21
46.20%	308	0.24
50.10%	334	0.26
56.25%	375	0.29
60.15%	401	0.31
66.15%	441	0.34

Natural Vegetation

$$A_s = 0.00209 \text{ m}^2$$

$$\text{Unit Area} = 1.4884 \text{ m}^2$$

$$\text{Surface Area (S)} = 0.001124 \text{ m}^2$$

Volumetric Percent Cover	Number of Plant Individuals	Lateral Cover (L_c)
4.80%	8	0.01
10.20%	16	0.02
15.00%	25	0.04
20.40%	34	0.05
25.20%	42	0.06
30.60%	51	0.07
35.40%	59	0.08
40.05%	67	0.09
45.60%	76	0.11
50.40%	84	0.12
55.20%	92	0.13
60.00%	100	0.14
65.40%	109	0.15
70.20%	117	0.16

Dowels

$$A_s = 0.0025 \text{ m}^2$$

$$\text{Unit Area} = 1.4884 \text{ m}^2$$

$$\text{Surface Area (S)} = 0.0025 \text{ m}^2$$

Volumetric Percent Cover	Number of Dowels	Lateral Cover (L_c)
5.00%	30	0.05
10.00%	60	0.10
15.00%	90	0.15
20.00%	120	0.20

APPENDIX B: CONVERSION OF VOLUMETRIC PERCENT COVER TO LATERAL COVER

		Artificial Vegetation												Natural Vegetation																	
		5.55%	10.65%	15.75%	19.80%	25.65%	31.05%	36.15%	41.25%	46.20%	51.15%	56.25%	61.20%	66.15%	4.80%	10.20%	15.00%	20.40%	25.20%	30.60%	35.40%	40.80%	45.60%	50.40%	55.20%	60.00%	65.40%	70.20%			
Artificial Vegetation Mean Velocities	Run	M1	0.90	5.10	5.75	5.64	5.43	5.96	6.21	6.81	3.60	4.20	4.58	4.55	4.72	5.10	0.02	0.05	0.08	0.10	0.13	0.15	6.84	6.80	7.13	7.01	5.77	4.40	4.79	5.27	
			0.50	4.89	5.52	5.45	5.21	5.69	5.87	6.29	3.31	3.77	4.20	4.21	4.38	4.81	6.40	6.35	6.68	6.53	5.38	4.18	4.52	4.94							
			0.08	3.93	4.43	4.39	4.22	4.53	4.65	5.01	2.57	2.84	3.10	3.20	3.31	3.70	4.68	4.61	4.86	4.75	3.93	3.01	3.27	3.59							
		M2	0.90	5.26	5.96	5.95	5.70	6.18	6.34	6.53	3.66	4.27	4.71	4.74	4.94	5.36	6.89	6.89	7.34	7.23	5.89	4.63	4.99	5.44							
	0.50		4.89	5.55	5.49	5.27	5.73	5.88	5.99	3.39	3.81	4.25	4.24	4.43	4.93	6.41	6.41	6.73	6.60	5.42	4.18	4.52	4.96								
	0.25		4.64	5.20	5.08	4.84	5.23	5.35	5.53	2.89	2.70	3.29	3.48	3.56	3.63	6.01	5.63	6.01	5.88	4.21	2.93	3.25	3.52								
	M3	0.08	3.41	3.37	2.35	1.84	2.15	2.18	2.02	0.30	0.29	0.34	0.52	0.47	0.49	4.45	4.45	4.43	4.30	3.32	2.31	2.57	2.83								
		0.90	5.36	6.05	6.02	5.80	6.29	6.53	6.67	3.73	4.28	4.71	4.74	4.87	5.20	6.63	6.63	6.98	6.78	5.50	4.41	4.74	5.18								
		0.50	4.87	5.50	5.44	5.24	5.68	5.94	5.99	3.42	3.90	4.27	4.31	4.51	4.90	6.19	6.19	6.55	6.33	5.11	4.16	4.41	4.80								
		0.25	4.60	5.13	4.93	4.70	4.89	5.10	4.82	2.46	2.76	2.89	2.82	2.92	3.09	4.37	4.37	4.76	4.51	3.57	2.67	2.79	2.89								
	0.08	3.26	3.46	2.77	2.12	2.04	2.00	1.94	0.46	0.31	0.37	0.40	0.40	0.44	2.82	2.82	3.15	2.56	1.63	0.62	0.89	1.14									
Natural Vegetation Mean Velocities	Run	M1	0.90	5.73	6.29	6.29	6.05	6.45	6.83	6.84	6.80	7.13	7.01	5.77	4.40	4.79	5.27	0.02	0.05	0.08	0.10	0.13	0.15	6.83	6.83	7.08	6.89	5.77	4.40	4.79	5.27
			0.50	5.00	5.51	5.51	5.31	6.03	6.40	6.43	6.40	6.35	6.68	6.53	5.38	4.18	4.52	4.94	6.49	6.49	6.68	6.53	5.38	4.18	4.52	4.94					
			0.08	4.00	4.37	4.37	4.20	4.42	4.68	4.70	4.68	4.61	4.86	4.75	3.93	3.01	3.27	3.59	7.08	7.08	7.34	7.23	5.89	4.63	4.99	5.44					
		M2	0.90	5.45	6.10	6.10	5.90	6.61	7.08	7.09	7.09	6.89	7.34	7.23	5.89	4.63	4.99	5.44	6.49	6.49	6.73	6.60	5.42	4.18	4.52	4.96					
	0.50		5.08	5.65	5.65	5.43	6.08	6.49	6.51	6.41	6.41	6.73	6.60	5.42	4.18	4.52	4.96	5.88	5.88	6.01	5.88	4.21	2.93	3.25	3.52						
	0.25		4.44	4.74	4.74	4.68	5.56	5.88	5.80	5.63	5.63	6.01	6.01	4.21	2.93	3.25	3.52	4.43	4.43	4.43	4.30	3.32	2.31	2.57	2.83						
	M3	0.08	3.82	3.79	3.79	3.32	4.26	4.64	4.62	4.45	4.45	4.43	4.30	3.32	2.31	2.57	2.83	6.65	6.65	6.98	6.78	5.50	4.41	4.74	5.18						
		0.90	5.12	5.64	5.64	5.37	6.11	6.65	6.69	6.63	6.63	6.98	6.78	5.50	4.41	4.74	5.18	6.23	6.23	6.55	6.33	5.11	4.16	4.41	4.80						
		0.50	4.74	5.20	5.20	4.97	5.73	6.23	6.28	6.19	6.19	6.55	6.33	5.11	4.16	4.41	4.80	4.14	4.14	4.37	4.51	3.57	2.67	2.79	2.89						
	0.25	4.05	4.41	4.41	3.88	3.55	4.14	4.27	4.27	4.37	4.76	4.51	3.57	2.67	2.79	2.89	3.38	3.38	3.53	3.53	1.63	0.62	0.89	1.14							
	0.08	3.38	3.69	3.69	3.53	2.66	3.13	2.95	2.82	2.82	3.15	2.56	1.63	0.62	0.89	1.14	0.02	0.05	0.08	0.10	0.13	0.15	0.02	0.05	0.08	0.10	0.13	0.15			

APPENDIX C: REGRESSION ANALYSIS AND LINE PLOTS

Artificial Vegetation @ 0.9m above the bed
SUMMARY OUTPUT

<i>Regression Statistics</i>	
Multiple R	0.984931032
R Square	0.970089138
Adjusted R Square	0.96893872
Standard Error	0.149203709
Observations	28

ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	1	18.7722053	18.77221	843.249436	2.41086E-21
Residual	26	0.578805413	0.022262		
Total	27	19.35101071			

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	0.029391202	0.179658151	0.163595	0.87131491	-0.339901412	0.398683816	-0.3399	0.398684
X Variable 1	0.957567014	0.032975482	29.03876	2.4109E-21	0.889784941	1.025349087	0.889785	1.025349

RESIDUAL OUTPUT

<i>Observation</i>	<i>Predicted Y</i>	<i>Residuals</i>
1	5.161950398	-0.041950398
2	5.094920707	-0.064920707
3	5.228980089	-0.088980089
4	5.793944627	-0.033944627
5	5.841822978	-0.101822978
6	5.573704214	-0.103704214
7	6.00460937	-0.19460937
8	5.717339266	-0.167339266
9	5.449220502	-0.139220502
10	6.03333638	-0.09333638
11	6.071639061	-0.091639061
12	6.311030814	-0.071030814
13	6.253576794	-0.083576794
14	6.368484835	0.361515165
15	6.454665867	0.425334133
16	3.495783793	-0.015783793
17	3.696872866	0.023127134
18	4.070324002	0.109675998
19	4.175656373	0.044343627
20	4.702318231	0.037681769
21	4.376745446	0.033254554
22	4.434199467	-0.054199467
23	4.692742561	0.027257439
24	4.65443988	-0.00443988
25	4.62571287	-0.13571287
26	4.798074932	0.231925068
27	4.893831634	0.046168366
28	5.114072047	0.145927953

Artificial Vegetation @ 0.5m above the bed
SUMMARY OUTPUT

<i>Regression Statistics</i>	
Multiple R	0.993824876
R Square	0.987687884
Adjusted R Square	0.987214341
Standard Error	0.087008048
Observations	28

ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	1	15.789895	15.78989	2085.741028	2.32863E-26
Residual	26	0.1968304	0.00757		
Total	27	15.986725			

	<i>Coefficients</i>	<i>Standard Err</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	0.493730435	0.0979259	5.041878	3.00905E-05	0.292440877	0.69502	0.292441	0.69502
X Variable 1	0.904959664	0.0198152	45.66991	2.32863E-26	0.864228884	0.94569	0.864229	0.94569

RESIDUAL OUTPUT

<i>Observation</i>	<i>Predicted Y</i>	<i>Residuals</i>
1	4.937082387	-0.077082
2	4.873735211	-0.053735
3	4.937082387	-0.017082
4	5.480058186	0.0099418
5	5.498157379	0.0118426
6	5.262867866	-0.002868
7	5.588653345	0.0213467
8	5.30811585	0.0518842
9	5.109024723	0.0009753
10	5.633901329	0.0260987
11	5.652000522	0.0479995
12	5.832992455	0.1070075
13	5.769645278	0.1703547
14	6.113529951	-0.17353
15	6.258323497	-0.218323
16	3.371502168	-0.051502
17	3.606791681	-0.086792
18	3.950676353	-0.100676
19	3.85113079	0.0988692
20	4.421255379	-0.011255
21	4.158817076	-0.028817
22	4.149767479	0.0102325
23	4.457453765	-0.007454
24	4.385056992	-0.015057
25	4.321709815	0.0282902
26	4.656544891	0.1534551
27	4.756090454	0.0239095
28	4.928032791	0.0819672

Natural Vegetation @ 0.9m above the bed
SUMMARY OUTPUT

<i>Regression Statistics</i>	
Multiple R	0.967775401
R Square	0.936589227
Adjusted R Square	0.93424068
Standard Error	0.23824092
Observations	29

ANOVA

	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	1	22.635109	22.63511	398.7952	1.06E-17
Residual	27	1.5324859	0.056759		
Total	28	24.167595			

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	0.14057297	0.2965918	0.473961	0.639338	-0.46798	0.749129	-0.46798	0.749129
X Variable 1	1.021915667	0.0511729	19.96986	1.06E-17	0.916918	1.126914	0.916918	1.126914

RESIDUAL OUTPUT

<i>Observation</i>	<i>Predicted Y</i>	<i>Residuals</i>
1	6.026807212	0.3231928
2	5.822424079	0.0375759
3	5.331904559	0.3180954
4	5.413657812	0.3863422
5	6.026807212	0.3431928
6	5.781547452	0.4184525
7	5.607821789	0.4621782
8	5.648698416	0.3713016
9	6.261847816	0.0581522
10	6.507107576	0.0818924
11	6.834120589	-0.0641206
12	7.028284566	-0.1382846
13	6.823901433	-0.0839014
14	7.120256976	-0.180257
15	7.028284566	-0.0582846
16	6.803463119	-0.1734631
17	7.222448543	-0.1424485
18	7.314420953	-0.134421
19	6.854558903	-0.0645589
20	7.273544326	-0.0535443
21	5.761109139	0.0088909
22	4.790289255	-0.2902893
23	4.545029495	-0.2350295
24	4.504152869	-0.2241529
25	4.749412629	-0.2394126
26	4.820946725	-0.2009467
27	5.147959739	-0.1879597
28	5.403438656	-0.1734387
29	5.464753596	-0.1647536

Natural Vegetation @ 0.5m above the bed
SUMMARY OUTPUT

<i>Regression Statistics</i>	
Multiple R	0.992254125
R Square	0.984568249
Adjusted F	0.983996703
Standard E	0.108921488
Observatic	29

ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>ignificance F</i>
Regressor	1	20.437206	20.43721	1722.639	5.36E-26
Residual	27	0.32032504	0.011864		
Total	28	20.757531			

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>ower 95.0%</i>	<i>pper 95.0%</i>
Intercept	0.019281298	0.13412446	0.143757	0.88676	-0.25592	0.294482	-0.25592	0.294482
X Variable	1.029346059	0.02480072	41.50469	5.36E-26	0.978459	1.080233	0.978459	1.080233

RESIDUAL OUTPUT

<i>Observator</i>	<i>Predicted Y</i>	<i>Residuals</i>
1	5.526282714	0.07371729
2	5.330706963	-0.230707
3	4.836620855	0.06337915
4	4.949848921	0.14015108
5	5.45422849	0.10577151
6	5.289533121	0.16046688
7	5.124837751	0.19516225
8	5.135131212	0.16486879
9	5.814499611	0.09550039
10	6.010075362	0.13992464
11	6.339466101	-0.0094661
12	6.524748392	-0.0547484
13	6.339466101	-0.0194661
14	6.627682998	-0.097683
15	6.49386801	0.01613199
16	6.277705338	-0.0977053
17	6.751204525	-0.1012045
18	6.772820792	-0.0628208
19	6.349759562	-0.0097596
20	6.710030682	-3.068E-05
21	5.27923966	0.10076034
22	4.435175892	-0.1551759
23	4.249893601	-0.1298936
24	4.126372074	-0.0763721
25	4.373415128	-0.0934151
26	4.424882431	-0.0448824
27	4.692512407	-0.0425124
28	4.929262	-0.009262
29	4.980729303	-0.0207293

VITA

Jennifer Booth was born in Calgary, Alberta, Canada, in 1981. Having many opportunities to travel and explore the outdoors from an early age, Jennifer began to question about earth's processes for a number of different environments. After graduating in 2000 from General Vanier Secondary School in Cornwall, Ontario, Jennifer moved to the University of Guelph to pursue a degree in International Development.

However, finding more interest in the geomorphology and hydrology lectures, she changed her major and rekindled her love for questioning earth processes. Originally finding a foothold in hydrology and fluvial transport systems, Jennifer later participated in a field research camp in the Great Basin Desert. Aeolian mechanics moved to the forefront of her interest and Jennifer found herself engulfed in an undergraduate thesis project regarding sediment trapping and vegetation. After completing a summer position as a field assistant in the Chihuahuan desert, Jennifer finished her Bachelor of Arts at the University of Guelph and moved to Baton Rouge to continue her education at Louisiana State University.

Working within a coastal environment at LSU gave Jennifer the opportunity to expand her horizons and study wind and wave interactions along the coast. She received the William G. Haag Award for best conference paper presented at the master's level in 2005. She was also awarded a COMA student paper award with her colleagues at the American Association of Geographers conference in 2006. Upon completion of her studies at LSU, she will return to the University of Guelph to pursue a doctoral degree and has been awarded an Ontario Government Scholarship for Science and Technology to do so.