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THE PHYSICAL EFFECTS OF VEGETATION ON COASTAL DUNE SYSTEMS IN FLORIDA

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EXECUTIVE SUMMARY

Although it has long been recognized that coastal plants serve to maintain and even develop sand dunes there has been surprisingly little study of the underlying aerodynamic processes. In regulating the development of Florida's coastal areas engineers in the Florida Department of Natural Resources Division of Beaches and Shores need to be able to make assessments of the relative roles of a wide range of vegetation types on the retention of sand. As a result of this need, a study has been conducted to establish the controlling physical relationships and to provide a quantitative method of determining the sand trapping capacity of coastal vegetation. The study was intended to advance our understanding of these subjects quickly and effectively. Consequently, this first phase of the work was directed toward the development of theory and methods of analysis using parameter measurements from the published literature. It is expected that subsequent research will provide other analyses and measurements based on the approach developed in this first phase.

There are several theories and predictive equations for sand transport by wind (i.e. aeolian transport) for loose, dry sand on a flat horizontal surface; exposed to a fully developed turbulent shear boundary layer. All contain empirical constants and coefficients to some degree. Recent studies have demonstrated that most of the competing relationships produce similar results. As a result the theory developed by Bagnold was adopted as the method of computing sand transport by the wind provided that the sand grain size, density, and sorting are known. Bagnold's equation relates the mass flux of sand to the friction velocity of the wind and this must be known (measured, or calculated).

Bagnold's equation is used to compute the sand transport on a flat open beach as a basis of comparison to changes caused by the interaction of vegetation with the air flow. These interactions are characterized by a three tiered boundary layer over and within the vegetated area. Above the plant

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canopy, a shear boundary layer similar to that over the open beach, is pictured. Typically the vegetation causes higher drag than bare ground so that there is a sharper vertical profile of the mean horizontal wind in this layer than the bare ground equivalent. The lowest portion of this velocity profile projects into the upper portion of the vegetation canopy.

Within the canopy the turbulence arises largely as a result of the air passing through the foliage. The vertical velocity profile is altered to an exponential shape matched at the top of the vegetation to the overlying shear boundary layer profile.

Near the ground there is a third zone within which another shear boundary layer is developed. Sand transport takes place in this layer.

A series of equations are formulated to represent these physical processes. They are used to compute the sand transported within, or beneath, a plant canopy for set wind conditions. These results are compared to corresponding bare ground results.

Much of the approach is related to previous research concerning air flow above and within crops and forests. Many of the controlling relationships are constrained by simplifying assumptions. These relationships also depend on the evaluation of air flow parameters which can only be experimentally determined. These measurements have not been conducted for coastal plants. In order to provide working estimates of these parameter values for coastal plant all accessible data concerning measurements made for all types of plants was assembled. The physical characteristics of both the measured and unmeasured types of plants were tabulated and used to assign aerodynamic coefficients to the coastal plants based on their similitude with the measured group.

The major portion of this study was devoted to developing a method of comparison of the sand transport in different types, sizes, and densities of coastal vegetation presuming a single plant type and a fully developed boundary layer for each analysis. However, the transitional boundary layer conditions were also considered and incorporated into a special analysis. This analysis is appropriate to the case of narrow lines of vegetation, oriented across the wind. The case of mixed plant assemblages is also considered.

Included in the recommendations for future work are: 1) Expansion of the approach to include larger horizontal scales and sloped terrain. 2) Development of better aerodynamic coefficients for coastal plants.

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INTRODUCTION

Natural coastal dune vegetation generally survives in an environment which requires special adaptation. Two features of this environment are the sandy, humus-poor soil and the high salt content of the air, soil and soil water. The plants which are adapted to this environment tend to stabilize its physical features by trapping and holding wind-blown sand.

The beneficial nature of coastal vegetation in trapping and holding wind-blown sand has long been recognized and there are a large number of qualitative statements to this effect in the literature (Jagschitz and Bell 1966, Savage and Woodhouse 1968, Gage 1970, Dahl et al 1975), often supported by observations. However, the physics of the interaction of coastal plants and sand transport has remained poorly studied. Without a quantitative study of these effects it is not possible to understand how effective different types and distributions of plants are in causing deposition of wind-blown sand and in preventing erosion.

For these reasons a study was conducted of the physical effects of vegetation on coastal dune systems in Florida. The study was proposed as an initial exploration of this subject and was therefore based on existing literature as opposed to field or wind tunnel work. The objectives of the project were:

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- carry out a comprehensive literature search concerning the natural dune plants of Florida, the role of vegetation in stabilizing sand dunes, and the theoretical understanding of the direct effects of vegetation on sand transport by wind;

-develop an understanding of the effect of the various physical attributes of plants in their relative abilities to trap and retain sand on, and near the beach;

- provide a basis of comparison for assessing the relative effectiveness of vegetation in promoting the stability and growth of coastal sand dunes;

- develop a procedure to predict the potential magnitude and rate of change intle_1178 sandred in coastal dunes as the result of changes in the vegetation.

The aim of this study is to provide coastal engineers and scientist working for the Division of Beaches and Shores with methods for assessing the effects of proposed changes in coastal vegetation on the natural functioning of the coastal systems. A major emphasis is on processes resulting in long-term sand storage which provides a buffer against erosion.

It was soon discovered that a natural division of processes occurs based on the characteristic coastal length scales under consideration. These generally divide into a local scale of features and processes acting over lengths on the order of 10s to 100s of feet and a coastal scale with lengths of thousands of feet to miles. Two factors influenced the study to concentrate on the local scale. First, most of the problems of interest to the Division of Beaches and Shores arise from individual lot permit issues and these lots are typically of the local length scale. Secondly, it proved feasible to develop an approach to evaluating the effects of vegetation on wind-blown sand transport at this scale in considerable detail. As a consequence, the major portion of this report is devoted to local scale processes, with coastal scale processes being treated only briefly towards the end.

DESCRIPTION OF PROCESSES

Near-Ground Atmospheric Flow

The atmosphere flows in response to pressure gradients resulting in the wind. The frictional effects of the earth's surface are confined to a zone (or boundary layer) which is generally less than a couple thousand feet in thickness. The major frictional processes occur in a subregion of this boundary layer where there is thought to be a constant mean horizontal shear stress. This layer is typically a few hundred feet thick.

If the mean wind speed ($u(z)$) is measured at several heights (z) in the lower portion of the atmospheric boundary and plotted they tend to yield profiles of similar form to that shown in Figure 1a. The rate of increase of wind speed with height ($\partial u/\partial z$) is greatest near the ground and decreases with height. Such curves appear as straight lines when the wind speed is plotted against the log of the height (Figure 1b). The general form of this relationship is,

$$u(z) = a \ln(z) + b$$

where a and b are independent of z. It is usual to replace b with $-a \ln(z_0)$ where z_0 is a roughness parameter equal to the small height at which the logarithmic equation predicts zero velocity. This is typically one order of magnitude smaller than the physical height of the surface roughness elements. From this it follows that,

$$u(z) = a \ln(z/z_0)$$

Differentiation of this equation with respect to z yields,

$$\frac{\partial u}{\partial z} = \frac{a}{z}$$

which shows that the vertical gradient of the wind is inversely proportional to the height above the ground. This has been taken to indicate that the dimension of friction-driven turbulent eddies is directly related to the distance above the surface because larger eddies can be expected to be more effective in vertical mixing than smaller ones.

Another useful parameter is the friction velocity (u_*) which is defined as,

$$u_* = (\tau/\rho)^{0.5}$$

where τ is the vertical shear of horizontal momentum in the boundary layer and ρ is the air density. This quantity has the dimension of velocity which explains the name 'friction velocity'.

The parameter "a" in the expression for velocity, is commonly assumed to be proportional to u_* and both are independant of height. The constant of proportionality is κ, called von Karman's constant, and has a value of 0.4.

$$a = u_*/\kappa$$

Thom (1975) states that the product κz can be identified with the mixing length (l_W) or effective eddy size at the level z, by the expression,

$$l_W = \kappa\ z.$$

With the appropriate substitution for the parameter a, the equation for the velocity profile in the constant stress frictional boundary layer becomes,

$$u(z) = (u_*/\kappa)\ \ln(z/z_0)\ .$$

When the value of von Karman's constant is included and the natural logarithm is replaced with the common logarithm this equation is written as,

$$u(z) = 5.75\ u_*\ \log_{10}(z/z_0)\ .$$

The Physics of Wind-Blown Sand

Our knowledge of aeolian, or wind-blown, sand transport dynamics has developed slowly as the result of research which has been of scattered intensity over the past 50 years. Much of what is presently known is based on empirical measurements and simplified dynamics. Recent field studies have shown that although there are competing theories they are similar and several produce results which show reasonable agreement with measured data (Horikawa et al 1986).

The process of aeolian transport of loose sand on a large flat horizontal surface is easily described. Gravity stabilizes the surface grains in their places against fluid forces which tend to entrain and move them. Therefore, there is a threshold wind intensity below which no sand transport occurs. Above this threshold individual grains are dislodged and put into various types of movement including upward and downwind displacement due to the fluid forces, downward movement due to gravity, and various bouncing, rolling and sliding motions. All this is generally called grain saltation.

The presence of grains saltating in the lower portion of the boundary layer changes its behavior. Figure 2 shows profiles of the mean horizontal wind speed for conditions below and above the grain entrainment threshold. The height ordinate is a log scale so the profiles appear as straight lines. The three profiles (corresponding to three different mean wind speeds) for sub-threshold conditions intersect with the height axis at a common point above the ground surface. This is taken as the base of the constant stress portion of the turbulent boundary layer. Below this, the forces of molecular viscosity become increasingly important in the so-called laminar sublayer. The height of the zero intercept of these profiles is the roughness height (z_0).

Figure 2 also shows profiles for three wind conditions which are above the grain threshold conditions. These also intersect at a common point called the focal point. This point is displaced upward from z_0 to a new height designated as z'. The focal point is also displaced outward from the ordinate by a speed designated as u'. The change of z_0 to z' as the grain movement threshold is exceeded indicates that the vertical divergence of stress in the boundary layer increases and wind energy is dissipated more rapidly per unit area of the sand bed.

A consequence of these changes in the structure of the boundary layer is that the equation for mean wind speed as a function of height,

$$u(z) = 5.75\, u_* \log_{10}(z/z_0) \qquad \{\text{below threshold}\}$$

is recast to,

$$u(z) = 5.75\, u_* \log_{10}(z/z') + u' \qquad \{\text{above threshold}\}.$$

Various empirical relationships have been developed from wind tunnel experiments that relate these flow parameters to characteristic sand grain parameters. Bagnold (1954) suggested,

$$z_0 = d/30$$

and Zingg (1952) proposed,

$$z' = 10\ d \quad \text{and}$$

$$u' = (894\ \text{cm/sec mm})\ d\ ,$$

where d is the sediment grain diameter.

Even though Zingg's equations are empirical they are based on extensive wind tunnel measurements. The above expression for z_0, z', and u' are not well studied but they are commonly applied. Some comfort may be taken from a recent review of aeolian sand transport theories and measurements by Horikawa et al (1986) which indicates reasonable agreement between measurements and computed transports based, in part, on these empirical relationships.

These equations permit the velocity profile relationship to be rewritten to solve for u_* in terms of a single wind speed determination at a known height and the mean sand grain size;

$$u_* = u(z)/\ 5.75\ \log_{10}(z/z_0) \qquad \{\text{no sand transport}\},$$

$$u_* = (u(z) - u')/5.75\ \log_{10}(z/z') \qquad \{\text{sand in transport}\}.$$

These expressions indicate that the wind conditions which define the threshold of grain movement should be expressed in terms of a critical value of the shear velocity (u_{*crit}). The vertical profile of the wind changes depending on the condition of the sand bed so that the shear stress applied to the bed cannot be directly associated with a unique wind speed.

Several investigators have developed methods to define and predict the values of the critical shear stress ($u_{*\ crit}$) needed to initiate grain transport (Bagnold 1941 and 1954, Iwagaki 1950, Horikawa and Shen 1960, Tsuchiya and Kawata 1975, and Nickling 1988). These relationships are also entirely based on empirical data. The one shown on Figure 3 from Horikawa and Shen (1960) is, in part, based on earlier observations by Iwagaki (1950) and Bagnold (1954), and provides an adequate summary of these observations. It relates $u_{*\ crit}$ to a parameter comprised of the square root of the product of the mean grain diameter and the grain density.

There are also several expressions available to compute aeolian sand transport once the threshold conditions have been exceeded. These are also based largely on measured data but have varying degrees of associated physical explanations. Horikawa et al (1986) reviewed these relationships and conducted a comparison based on available measured data. They found that the various expressions derived by Bagnold (1941 and 1954), Nakashima (1979), Kawamura (1951), and Horikawa et al (1983) all produce similar results and are in reasonable agreement with measurements.

The physics of Bagnold's equation for aeolian sand transport are readily explained. Figure 4 shows a definition sketch of a control volume in which grain saltation occurs. The volume has a unit width and a length (L) defined by the average distance a saltating grain moves in a unit time increment (Δt). That is,

$$L = U_s \Delta t,$$

where U_s is the mean grain speed. Bagnold likened the aeolian sand transport process to the ordinary process of sliding friction and generalized the details of the various fluid forces acting on the grains by assuming that they are proportional to the shear stress per unit area (τ_0). Thus the net downward force acting on the sum of the dispersed grains in the control volume is proportional to the fluid shear stress acting on the bed. The net downward force acting on the dispersed saltating grains (f_d) is,

$$f_d = Mg = (Q\Delta t)g,$$

where Q is the mass flux of grains through the box. The fluid shear stress acting on the bed (f_s) is the shear stress per unit area multiplied by the area of the base of the control volume,

$$f_s = \tau_0(U_s\Delta t).$$

If K is a constant of proportionality then Bagnold's relationship can be expressed as,

$$(Q \Delta t)g = K \tau_0(U_s\Delta t),$$

or

$$Q = K\ (\rho_a/g)(\tau_0/\rho_a)U_s.$$

where ρ_a is the air density. Using the definition of the shear velocity (u_*) this becomes,

$$Q = K\ (\rho_a/g)\ u_*^2\ U_s.$$

If it is assumed that the average grain speed in the control volume is proportional to the shear velocity

$$U_s = k\ u_*,$$

then Bagnold's relationship becomes,

$$Q = K\ k\ (\rho_a/g)\ u_*^3.$$

Bagnold (1954) used experimental data to show,

$$K\ k = B\ (d/D)^{0.5}$$

where B is a standard reference grain diameter of 0.25 mm and B is a parameter controlled by the sand size gradation (sand size frequency distribution). He offers the following:

B = 1.5	uniformly graded sand,
B = 1.8	naturally graded sand, and
B = 2.8	broadly graded sand;

to which Cooke and Warren (1979) have added,

B = 3.5	for pebbly sand.

A substitution produces Bagnold's classic equation,

$$Q = B\ (\rho_a/g)(d/D)^{0.5}u_*^3$$

This equation is commonly used for computing aeolian sand transport but it must be kept in mind that it is derived for loose dry sand on a flat horizontal surface. Tsoar (1974), Hunter et al (1983), and Hotta (1984) report marked increases in threshold velocities and decreases in sand transport flux due to soil moisture in excess of 1%.

Nickling (1984) has examined the effects of surface salt concentrations on the grain entrainment threshold values. He reports that even very low concentrations significantly increase the entrainment threshold. Small scale bedforms such as sand ripples also alter the threshold and transport relationships. Larger scale slopes, such as those associated with coastal dunes effect aeolian transport in several ways. First the slope can either increase or decrease the entrainment threshold values depending on their alignment relative to the wind. These slopes also create horizontal pressure gradients due to form drag and these gradients alter the structure of the near-ground vertical velocity gradient. As the profile of the lower turbulent boundary layer changes so does the magnitude of the shear stress applied to the sand bed.

These complicating effects have been studied to varying degrees but there is no complete theory currently available which allows comprehensive treatment of their combined effects. In the absence of this it is usually best to evaluate problems using a simple theory such as Bagnold's while making allowances for the untreated factors.

Air Flow in a Plant Canopy

In a previous section the idea that the characteristic scale of turbulent eddies in a shear flow is controlled by the proximity of the ground was presented. The logarithmic mean velocity profile follows as a consequence of this 'structure' to the turbulence. Air flow through a vegetated area is different because the plants create turbulent wakes which are the dominant eddies within most canopies. Both the intensity and the scale of the turbulence is changed by the plants.

Clearly there must also be regions above the plants and very close to the ground where the structure of the turbulence is not dominated by the plants and resembles the basic shear flow conditions. This means that there should be at least three sub-regions in the turbulent boundary layer. Well above the plant canopy the flow is such that the stress in constant, similar to that over bare ground but adjusted to a greater roughness height.

This sub-region is coupled to the boundary layer flow within the plant canopy whose turbulence is greatly influenced by the vegetation. Finally there is the near-ground sub-region where the scale of the turbulent eddies is again mainly controlled by the proximity of the ground and where a second constant stress layer occurs. Transition regions can be expected between these sub-regions.

Inoue (1963), Cionco (1971), Thom (1975), and others have examined the dynamics of turbulent flow in vegetation canopies. They have demonstrated that for a simple steady and fully developed flow with a neutrally-stable density structure, which is not influenced by adverse horizontal pressure gradients and is moving through a canopy with a nearly uniform vertical distribution of plant material, the vertical velocity profile has an exponential shape. This can be shown with the following explanation.

There are two types of shear stresses acting on the fluid in the control volume. One at the boundary due to the surrounding fluid. The other is distributed through the control volume and is due to the vegetation. Because the shear forces on the fluid due to vegetation are distributed (assumed uniformly) throughout the canopy it is convenient to treat them as "body" forces. The force per unit volume is thus:

$$\text{Shear Force/unit vol.} = \text{Shear Stress/unit depth}$$

$$= 1/2\ C_d\ \rho\ A\ u^2$$

where

C_d ≡ drag coefficient

ρ ≡ mass density of air

A ≡ vegetation surface area (all the leaves and branches) per unit volume

u ≡ horizontal velocity.

A simple force balance on the fluid within the control volume (in the absence of horizontal pressure gradients) results in

$$\tau + \frac{d\tau}{dz}\,\Delta z - \tau = \frac{1}{2}\,C_d\,\rho\,Au^2\,dz$$

or

$$\frac{d\tau}{dz} = \frac{1}{2} C_d \rho A u^2$$

where

$\tau \equiv$ the fluid shear stress acting on the fluid in the control volume at the lower boundary.

If we now express τ as

$$\tau = K_w \frac{du}{dz}$$

and K_w as

$$K_w = \ell_w^2 \frac{du}{dz}$$

where

$K_w \equiv$ eddy viscosity and

$\ell_w \equiv$ mixing length in z-direction

then the above equation becomes

$$\frac{d\tau}{dz} = \frac{d}{dz} \left[\ell_w^2 \left(\frac{du}{dz}\right)^2 \right] .$$

If ℓw is approximately constant as suggested by velocity and turbulence measurements within canopys

$$\frac{d\tau}{dz} = \ell_w{}^2 \left(2\frac{d}{dz}\right) \frac{d^2u}{dz^2}$$

$$= \frac{1}{2} C_d \rho A u^2$$

or

$$\frac{du}{dz} \left(\frac{d^2u}{dz^2}\right) = \frac{\rho C_d A}{4 \ell_w^2} u^2 .$$

Let $C \equiv \dfrac{\rho C_d A}{4 \ell_w^2}$ and assume that $C \neq f(u,z)$.

Then $$\frac{du}{dz}\left(\frac{d^2u}{dz^2}\right) = Cu^2$$

which is a second order, nonlinear, ordinary differential equation. The solution should be of the form,

$$u = K'e^{rz} .$$

Taking the appropriate derivatives,

$$\frac{du}{dz} = K're^{rz} \qquad \text{and} \qquad \frac{d^2u}{dz^2} = K'\ r^2e^{rz}$$

and substituting these into the ODE results in

$$(K're^{rz})(K'r^2e^{rz}) = C(K'e^{rz})^2$$

or

$$K'^2r^3e^{2rz} = CK'^2e^{2rz}$$

or

$$r = C^{1/3} = \left(\frac{\rho Cd\ A}{4\ell_w^2}\right)^{1/3}$$

so

$$\tau = \left(\frac{1}{4}\rho C_d A\ \frac{1}{\ell_w^2}\right)^{1/3}.$$

Thus

$$u = K'e^{rz} = K'\ \exp\left(\frac{\rho Cd\ A}{4\ell_w^2}\right)^{1/3} z \quad .$$

The boundary conditions are,

$$u_{(z=H)} = u_{(H)}$$

$$u_{(z=H)} = u_{(H)} = K'e^{rH}$$

or

$$K' = u_{(H)}\ e^{-rH}$$

and

$$u = u_{(H)} e^{r(z-H)} = u_{(H)} e^{rH(z/H-1)}$$

let $rH \equiv \alpha$

$$u = u_{(H)} e^{\alpha(\frac{z}{H}-1)}$$

where

$$\alpha = H\left(\frac{1}{4}\ \rho\ C_d A\ \frac{1}{\ell_w^2}\right)^{1/3} .$$

In this analysis the leaf area density (A) combined with the plant bulk aerodynamic drag coefficient (C_d) are used to parameterize the plant's frictional effects. The leaf area density can be determined from a more standard botanical (and agricultural) parameter known as the leaf area index (LAI) which is the sum of the area of one side of all of the leaves on a plant divided by the lot area (ie. total area of ground surrounding the plant). The leaf area density can be evaluated by dividing the LAI by the average plant height (H). This is also designated the PAI so that,

$$PAI = A/2.$$

The presence of the vegetation and the air moving through it effects the overlying boundary layer conditions. As illustrated on Figure 5 the vertical profile of the wind has a logarithmic profile starting a short distance above the top of the vegetation. Cionco (1971) performed regression analysis on numerous measured wind profiles above different types of vegetation and established that they could be fit with the same logarithmic function as an ordinary shear profile, provided that a zero plane displacement, d, is introduced. Using this parameter the equation of the mean horizontal velocity profile above the vegetation becomes,

$$u(z) = (u_*/\kappa)\ \ln((z-d)/z_0))$$

The zero plane displacement is typically a major fraction of the vegetation height. The roughness parameter (z_0) tends to be considerably higher for vegetation than for bare ground indicating that the vertical divergence of horizontal momentum above the vegetation is higher.

Bruin and Moore (1985) have developed an expression for the velocity profile in the transition region between the top of the exponential wind profile in the vegetation canopy and the overlying logarithmic zone. This transition zone is thought to extend to a distance of about twice the average plant height (H) above the ground over tall vegetation such as trees. However, this transition zone is not well studied and it is common practice to match the logarithmic and exponential velocity profiles presuming a sharp interface at the top of the vegetation.

The near-ground constant shear sub-region of the boundary layer is poorly studied. No published measurements have been found for this zone. However, the measured velocity profiles within plant canopies given in Cionco (1971) indicate that the exponential profile extends from the top of the vegetation to about 15% of its height. Although the relationship between the thickness of the near-ground logarithmic layer and plant parameters certainly contains planting density, vertical foliage distribution, and other factors in addition to plant height, this simple estimate is adequate as an initial estimate.

In summary, the shear-dominated atmospheric boundary layer in a fully developed flow (remote from the boundaries of the vegetation) is characterized by three sub-regions which can be described by either logarithmic or exponential velocity profiles which match at defined levels. The aerodynamic effects of the vegetation can largely be represented by three parameters: 1) the roughness length (z_0), 2) the zero plane displacement (d), and 3) the attenuation parameter of the exponential profile (α).

As will be discussed later, it is necessary to know these parameters for the particular vegetation of interest because they vary significantly for different plants. There are no measurements in the literature for coastal vegetation so the principal of similarity, which is commonly used in studying flow phenomena, has been resorted to for estimates of values for coastal vegetation.

A sensitivity analysis can be used to establish the relative importance of the vegetation aerodynamic parameters in evaluating changes in the shear stress applied to the ground and hence the change in sand transport relative to bare ground. The wind profile equations are combined and written so the wind speed at the top of the near-ground logarithmic layer (u_g) is expressed in terms of the vegetation parameters and the wind speed (u_{ref}) at a reference height (z_{ref}) high above the plant canopy. That is,

$$u_g = \frac{\ell n\ ((H-d)/z_o)\ \exp\ (-0.85\alpha)}{u_{ref}[\ell n((z_{ref}-d)/z_o)]} \quad .$$

This is differentiated with respect to the vegetation aerodynamic parameters.

$$\frac{\partial u_g}{\partial \alpha} = -\frac{0.85}{u_{ref}}\left(\frac{M}{N}\right) \exp\ (-0.85\alpha)$$

$$\frac{\partial u_g}{\partial z_o} = -\frac{z_o}{u_{ref}}\ \frac{[\ell n\ ((u_{ref}-d)/(H-d))]}{N^2}\ \exp\ (-0.85\alpha)$$

$$\frac{\partial u_g}{\partial d} = -\frac{\exp\ (-0.85\alpha)}{u_{ref}}\ \frac{[(N/(H-d)) - (M/(u_{ref}-d))]}{N^2}$$

$$\frac{\partial u_g}{\partial H} = -\frac{\exp\ (-0.85\alpha)}{u_{ref}\ (H-d)\ N}$$

where, $M = \ell n\ ((H-d)/z_o)$

$N = \ell n\ ((u_{ref}-d)/z_o)$.

When these partial derivatives are evaluated for extreme parameter values and a 50-m reference height, it was determined that the plant roughness parameter (z_0) is more important than the exponential velocity profile attenuation parameter (α). The zero plane displacement (d) and plant height (H) are less important than (α). This provides some guidance concerning the application of similarity-based comparisons between plants where measurements are available (generally crops and forests) and coastal plants.

The process of estimating the vegetation aerodynamic parameters for the coastal plants of Florida, and the resulting values, are given in Appendix A.

METHODS OF ANALYSIS

The role of vegetation in trapping sand and preserving sand storage within beach and dune systems can be analyzed using the concepts explained in the previous section. In many cases there is a rapid transition of near-ground wind velocity and boundary shear stress from bare sand to a vegetated zone. At the vegetation line there is a transition width in which the boundary layer exhibits nonuniform conditions as it adjusts to the presence of the vegetation. This transition region has a length on the order of 10 to 30 times the average vegetation height. This may be a distance of only a few 10s of feet for short grass and considerably longer for coastal forests. Therefore, there are two major conditions to consider. Broad zones of coastal vegetation permit the re-establishment of uniform flow conditions. Narrow vegetation zones only exhibit non-uniform flow conditions.

Fully Developed Flow

The fully developed flow case provides a good beginning for the analysis of how vegetation brings about changes in aeolian sand transport for several reasons. First, it provides a relatively simple way to address such basic questions as: How great a change in sand transport is caused by various types and densities of vegetation? What spacing or density of one vegetation type is equivalent to the spacing of another vegetation type with respect to its capacity to trap and retain wind blown sand? How do the sand trapping capacities of various vegetations change with wind speed and plant spacing? To what degree can a coastal forest be thinned out to provide a better view without seriously impacting the sand trapping capacity of the natural condition?

A second reason for concentrating on the analysis of uniform flow conditions is that they have been more fully studied in agricultural and military applications so that there is a body of knowledge that can be adapted for application to coastal engineering problems. There is also a substantial difference in the approach that agricultural scientists have taken to uniform and non-uniform conditions with the former having more rigor.

Figure 6 illustrates a simplified version of the envisioned conditions. As the air flow enters the zone of vegetation the near-ground flow is changed as the boundary layer (b.l.) establishes a new equilibrium. If the wind is strong enough to transport sand on the beach, and the vegetation causes this transport to cease, then deposition will occur in the transition zone. A similar, but reversed pattern develops on the downwind side of the vegetation zone. Here erosion can occur when the upwind sand supply is blocked by the vegetation. Clearly these general patterns will reverse for an offshore wind.

In order to address the types of questions exemplified in the introduction to this section a straightforward method of analysis can be applied. Figure 7 provides a definition sketch. The problem is started by specifying a 10-m wind speed. This wind speed, either measured at, or corrected to, the height of 10 m above the ground is used because it is a standard measurement used by most meteorologists. The mean sand grain size, the sand size gradation, and the sand grain density must also be specified as environmental inputs.

Several vegetation parameters must also be known. These include the average height, characteristic plant spacing, spacing or density of plant in the area of interest, and the vegetation aerodynamic parameters (ie. z_0, d, and α). The vegetation aerodynamic parameters are not available from the literature or previous studies but estimates for these are available in Appendix A of this report for most of Florida's common coastal plants.

The 10-m wind and sediment information are used to compute the fluid shear stress applied to the sand bed by the wind and to compare this to the critical shear stress for grain entrainment. If this is not exceeded then the analysis is not of further interest. If the threshold is exceeded then a second computation is made using the new roughness parameter (z') to compute the friction velocity (u_*). This is used to compute the sand mass transport flux using Bagnold's equation. This provides the bare sand transport rate as a basis of comparison.

The logarithmic velocity profile equation is then used to calculate a reference wind speed (u_{ref}) high above the ground surface (a reference height of 50 m is convenient) based on the 10-m value. It is reasonable to assume that this value will remain unchanged over the vegetation, at least for local scale analyses.

The 50-m wind speed provides a starting point for the analysis of air flow over and within the vegetation canopy. The vegetation parameters z_0 and d are used with the modified velocity profile equation to compute the wind speed at the top of the vegetation (u_H). This can be used with the exponential velocity profile and the vegetation attenuation parameter (α) to calculate the velocity at the level of the top of the near-ground log layer ($z = 0.15H$). Finally, the shear velocity can be calculated with another application of the logarithmic velocity profile so that Bagnold's equation can be used to compute the mass flux of wind blown sand in the vegetated area.

Transitional Flow

Although the procedures for analyzing the effects of coastal vegetation using vertical wind profiles and uniform flow conditions are quite useful in quantifying the effects of different plant types and densities on aeolian sand transport, deposition and erosion, it is clear that the width of many coastal vegetation zones is not sufficient for this type of analysis to be entirely satisfactory. This is particulary true for taller vegetation as the width of the transition regions is typically 20 to 30 times the plant height. For these reasons a method has been developed to account for long narrow vegetation zones, generally parallel to the coast. These zones may be either natural or planted. They tend to look and function like the windbreaks and shelter belts common in inland agricultural areas. Again, there is no published information regarding the physical effects of these narrow zones on the coastal environment and the information which has been used is adapted from the agricultural engineering literature.

The use of vegetation as windbreaks and shelter belts dates from the time of the ancients and is still widely used in agriculture to shelter crops from strong winds that inhibit growth. They are also used to reduce evapo-transpiration losses or to enhance O_2 and CO_2 exchange, the former by reducing the turbulence in the sheltered area and the latter by increasing it with appropriately designed windbreaks. Consequently, there have been many studies of windbreaks and different types of optimizations have been sought. One common definition of an optimized windbreak in agricultural engineering is that which provides the greatest near-ground reduction of wind speed over the longest downwind distance. This is a definition which promotins sand retention in the coastal environment and thus, is adopted for these analyses.

In order to understand why a narrow line of vegetation (or a single sand or snow fence) is quite effective in trapping wind blown sand it is necessary to understand its effect on the atmospheric boundary layer. The actual effects are complex and no analytic solution of the governing equations has been developed. As a result, a combination of wind tunnel experiments, field measurements, and some numerical modeling have been used to develop a descriptive understanding of the underlying processes. Figure 8 shows the pattern of developing boundary layers which form as the result of a low narrow, wedge-shaped non-porous barrier in a thick boundary layer flow (ie. the thickness of the boundary layer is many times the height of the barrier). Plate (1971), and many others, have pointed out that the flow disturbance is very dependant on the upstream velocity profile, well before it encounters the barrier. A simple uniform logarithmic velocity profile is pictured in Figure 8 as an initial condition.

The flow disturbance begins a distance upstream of the barrier (typically 3 to 5 times the height of a non-porous barrier). A persistent counter-flowing eddy often forms upwind of the barrier. A zone of flow separation begins at the top of the barrier and extends many times the height of the barrier downstream. This zone of separation is outlined by a streamline defined by,

$$u_b/u_{inf} = 0.5,$$

where u_b is the velocity in the lee of the barrier and u_{Inf} is the velocity at a corresponding height in the undisturbed boundary layer upstream of the barrier (Plate, 1971). There is a transition region, centered on this bounding streamline, between the region of barrier influence (#2 on Figure 8) and a 'bubble' of sheltered air flow (#6 on Figure 8) in the lee of the barrier. The point where the bounding streamline intersects the land surface is defined as the <u>reattachment point</u>. This marks the downwind limit of most zones of interest in agricultural engineering because most of the sheltering occurs upwind of the reattachment point. However, from the point of view of understanding coastal processes it must be noted that the region of the re-establishing boundary layer (#3 on Figure 8) is still an area where the near-ground wind field is substantially altered from the undisturbed upwind reference condition. This means that the barrier can exert an influence on the sand transport patterns on the downwind lengths comparable to the coastal length scale.

Several other features shown on Figure 8 are significant. As the air flow encounters the region of influence of the barrier it is deflected upward and over the sheltered 'bubble'. Indeed, most non-porous barriers create a counter-flowing eddy on their upwind sides which has a near-ground flow opposite the regional wind direction. In strong winds the sand transport is arrested with the deposition taking place several barrier heights upwind.

Downwind of a non-porous barrier another counter-flowing eddy forms in the sheltered bubble. In extreme cases this flow is strong enough to transport sand in the direction opposed to the regional wind and to form a blow-out depression. It has also been noted that the reattachment point is relatively close to the barrier (about 10 H) if it is non-porous.

Narrow belts of vegetation such as windbreaks and shelter belts can be very dense and thus approach the condition of a non-porous barrier. However, more generally, they have varying degrees of porosity and therefore provide 'leaky barriers'. Although the overall pattern of boundary layer disturbances shown on Figure 8 is generally also valid for porous barriers, there are some important differences.

One difference is that the air flow leaking through the barrier reduces the velocity contrast above and below the streamline bounding the sheltered bubble and thus the amount of shear-driven turbulence in the transition region is reduced. This has the effect of actually reducing the turbulent exchange of horizontal momentum across the bounding streamline and stretching out the downwind extent of the sheltered region. Furthermore, the porous barrier substantially reduces the magnitude of the pressure difference across the barrier which further contributes to the lengthening of the sheltered region. This also promotes the breaking down of the counter-flowing eddy in the sheltered bubble. The counter-flowing eddy upwind of the barrier also vanishes as the pressure difference across the barrier is reduced.

Plate (1971) quotes classic field studies by Nageli (1941) and wind tunnel experiments by Blenk and Trienes (1956) which showed that, for a maximization of near-ground wind speed over the longest downwind distance, a medium barrier porosity (30 - 50%) is needed. The zone of at least 20% reduction in wind speed near the ground extends about 25 H in these conditions (Robinette 1972). As the porosity of the barrier is decreased the magnitude of the reduction of near-ground wind speed tends to increase, and eventually a counter-flowing eddy develops in the sheltered bubble. At the same time, the increased pressure gradients due to the reduction in barrier porosity cause the point of reattachment to move closer to the barrier and the inclination of the separation streamline, as it approaches the ground near the point of reattachment, also increases. The downwind length of the sheltered zone is reduced.

On the other hand, if the porosity of the barrier is increased from the optimum 30-50% level, the downwind length of the sheltered zone increases to a maximum at about 35 H but the reduction of the near-ground velocity becomes increasingly negligible. These patterns are shown in a general way on Figure 9.

The bottom panel (D) of Figure 9 illustrates another feature of vegetation wind barriers. If they are quite narrow and lack near-ground foliage, they can cause a near-ground jet to form. When this effect is strong it can lead to scour of the sand surface beneath the vegetation and may even threaten the health of the vegetation.

These observations of the behavior of vegetation windbreaks are in general agreement with studies of sand, and snow fences. Hotta et al. (1987) provide a good review of the literature on both field and wind tunnel experiments with snow fences. No really comprehensive study has been carried out in a way that permits identification of the optimum porosity to create the greatest near-ground wind reduction over the longest downwind length. Different investigators used fences with different discrete slat arrangements along with various sand sizes, wind regimes, fence alignments, experiment durations, and measurement methods (Tani 1958, Kimura 1957, Nishi and Kimura 1966, Jagschitz and Bell 1966, Monohar and Bruun 1970, Savage 1963, Woodhouse and Savage 1969, Gage 1970, Dahl et al. 1975, Phillips and Willetts 1979, and Iversen 1981). These studies show that sand fences (and snow fences) act like vegetation wind barriers so that the most protection is effected when the counter-flow eddies are minimized, the width of the sheltered area is long and the effective wind reduction is acceptibly high to promote dune growth. This occurs when the fence porosities are in the 30-50% range.

As noted earlier, there is a problem in combining the approach used for analyzing the uniform flow conditions to that used for transitional flows because the researchers studying crop air exchanges and windbreaks have taken different approaches. Although there are scattered detailed studies of specific conditions that have been carried out with rigor (eg. the application of numerical models) there is no consistent basis of comparison.

In the absence of an established common basis for quantifying the attenuation of wind on sand transport by continuous and narrow vegetation belts, a combined approach was developed. The basis of this approach rests on the common observation that greatest sheltering is developed by a wind break with a 30-50% porosity and this is similar to the vegetation density which causes maximum attenuation in a large field of vegetation. This provides a link to combining the largely judgement-based assessment of a wind barrier's porosity used by one group of agricultural scientists with the more quantitative measures developed in the numerical model of Pereira and Shaw (1982) which associates the drag parameters with the product of the plant drag coefficient and the leaf area density (C_d.PAI).

The ratios of the vegetation aerodynamic parameters z_0/H and d/H are used to estimate the product of C_d.PAI for the observed spacing of plants in a wind break. This value is then compared to the value associated with the greatest drag (ie. the highest zo/H). When the estimated product for the observed spacing is above the point of greatest drag then the length of the sheltered zone is reduced proportionally from 20H to 10H depending on the ratio of the difference between observed and maximum common spacing to the maximum common spacing. On the other hand, if the estimated product C_d.PAI is less than that for maximum drag then the wind attenuation is adjusted in the same way that it is for the fully developed flow case and the maximum sheltered length is lengthened towards a maximum of 35H.

The result of the analysis is a sand transport rate calculated for the sheltered area and compared to the bare sand case. The length of the sheltered area is also calculated.

Some auxillary information is of value in using the results of the above calculations. If a line of vegeation parallel to the beach is shown to be an effective windbreak then the effects of natural or man-made gaps should be carefully considered. Such gaps will only degrade the effectiveness of the vegetation line and if they are wider than several times the average plant spacing, they can cause a funneling of the near ground wind speed. Robinette (1972) indicated that such funneling can increase the wind speed immediately upwind of the gap by about 20%. This can be sufficient to cause a local scour hole with a width approximately equal to the gap in the line of vegetation.

All of this shows that even narrow zones of vegetation can be quite significant in contributing to long sand retention on the upper beach and in the dune system.

Effects of Local Slopes and Terrain

Up to this point there has not been mention of how slopes and terrain effect the analysis of the physical effects of vegetation on sand transport and dune systems. The effects are rather complex. Furthermore, these effects have been routinely avoided by researchers concerned with the attenuation of the wind by crop and forest canopies because they needlessly complicate experiments. It is, however, necessary to discuss these effects, at least qualitatively so that proper judgement can be used in applying the methods of analysis described in this report.

If a wind is directed onshore across a broad and flat beach it will develop a logarithmic velocity profile. When the air flow encounters a slope behind the beach the vertical structure of the boundary layer changes. The slope introduces form drag which is realized as a pressure gradient. As the air flows upslope the streamlines converge, the flow accelerates, and the pressure falls. Hence, there is a pressure gradient in the direction of the upslope flow which tends to further accelerate it. This favorable pressure gradient exists close to the ground so that the increase in velocity is not uniform with height. The vertical velocity profile is no longer a simple logarithmic function and the methods for analyzing wind attenuation in plant canopies and aeolian sand transport, which depend on a simple, predictable form of the vertical velocity profile, can no longer be rigorously applied.

Figure 10, taken from Bowen and Lindley (1974) illustrates the near-ground over-speeding effect from measurements made on a 13 m high slope of 26^0 and a nearly vertical cliff 9.5 m tall. The over-speeding was confined to a height of about twice the ground level difference (z'') and extends about 12 z'' downwind of the slope top. These results are qualitatively similar to what can be expect for other forms of local relief but accurate predictions depend on many factors including the wind speed, the roughness of the ground upwind of the toe of the slope, the density stability of the boundary layer, whether the slope is vegetated, etc.

There are many other effects of local topography which affect the wind speed and its vertical profile. The wind is often funneled into gullies and low areas, it is disturbed by large obstructions such as buildings, and the air flow can become detached at the crest of dunes causing a counter-flowing eddy in the lee. All of these factors are too complex to be treated in a comprehensive analytical method. The engineer or scientist is left to use the analysis techniques presented in this report along with good judgement in applying them to complex real problems.

Coastal Scale Effects

In evaluating the physical effects of vegetation in coastal areas it can be important to consider large scale processes which may be altered as a result of changes in vegetation. Ideally, there should be an analytic method which predicts sand transport, erosion, and deposition by the wind over zones with length scales of several thousand of feet. This method would be able to account for the changes in the near-ground air flow brought about by both the topography and the differences in the vegetation. Of course, the development of this procedure constitutes a rather large undertaking and is not available at this time. However, there have been many studies which address elements of this procedure and which provide insight into the results that are possible. A starting point involves considerations as simple as: "From the point of view of preserving the coasts against long term erosion, what physical features should be considered a dune"? "What combinations of winds and sand transport cause and maintain coastal dunes"? "How does vegetation in one part of a dune field effect the air flow long distances downwind"?

A reconnaissance was made to evaluate the type of features which can be designated as dunes as a first step in addressing these coastal scale processes. The viewpoint adopted was not purely that of a coastal engineer or coastal geomorphologist who might tend to restrict the term dune to only those features which originate solely as a result of aeolian processes. Instead, the consideration was based on the idea that any feature which tends to collect and retain wind-blown sand can be included in the pragmatic definition of the term 'dune'.

Florida Department of Natural Resources beach topographical profiles were obtained and plotted for Walton, Manatee, Charlotte, Collier, Dade, St Lucie, Brevard, Flagler, and Nassau counties as a sample of the general coastal environments around Florida. A detailed description of the analyses of these data is presented in Appendix D. The analysis supported a classification of the dune, and dune-like, features as being represented in five general categories which bear little resemblence to the classical dune forms common to desert areas. These five classes are: 1) multiple parallel to sub-parallel sand ridges generally aligned with the shoreline, 2) a single very elongated ridge parallel to the beach, 3) one or more elongated ridges atop the low wave-cut cliff or bluff behind an active beach prism, 4) low hummocky sand hills, often with nearly irregular plan-view patterns, 5) coastal relief highly modified by roads, structures, and other unnatural features. The characteristic dimensions and slopes of these features were tabulated as a first step in determining methods for rigorous study of air flow and vegetation distributions on the coastal length scale. These data are included in Appendix D. The analysis of coastal scale processes was delayed for a future phase of this work in agreement with the Division of Beaches and Shores contract technical representative to allow substantial effort to be directed at the local scale processes.

FIGURES

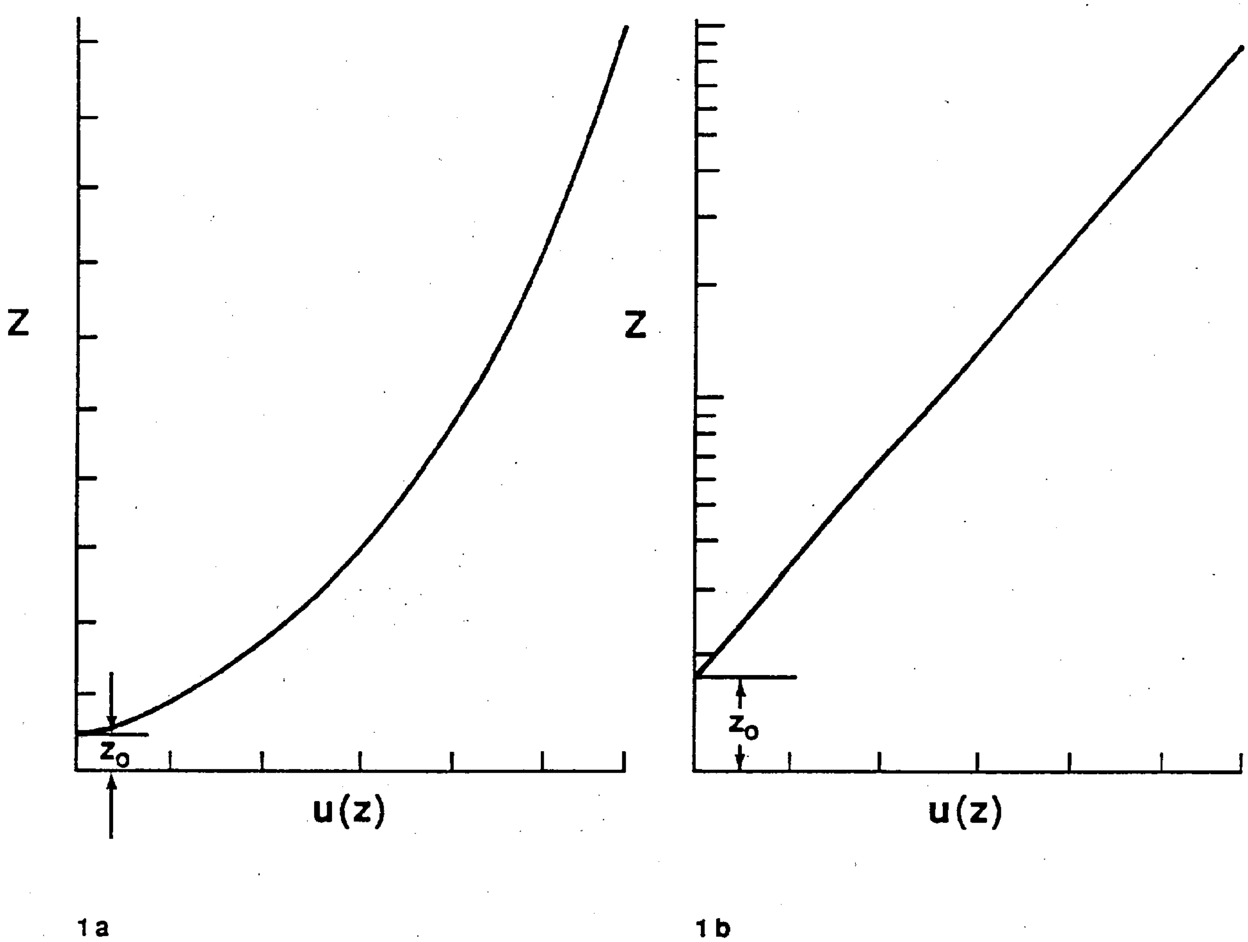

Figure 1 - The logarithmic velocity profile as a linear (a) and a semi-log plot (b)

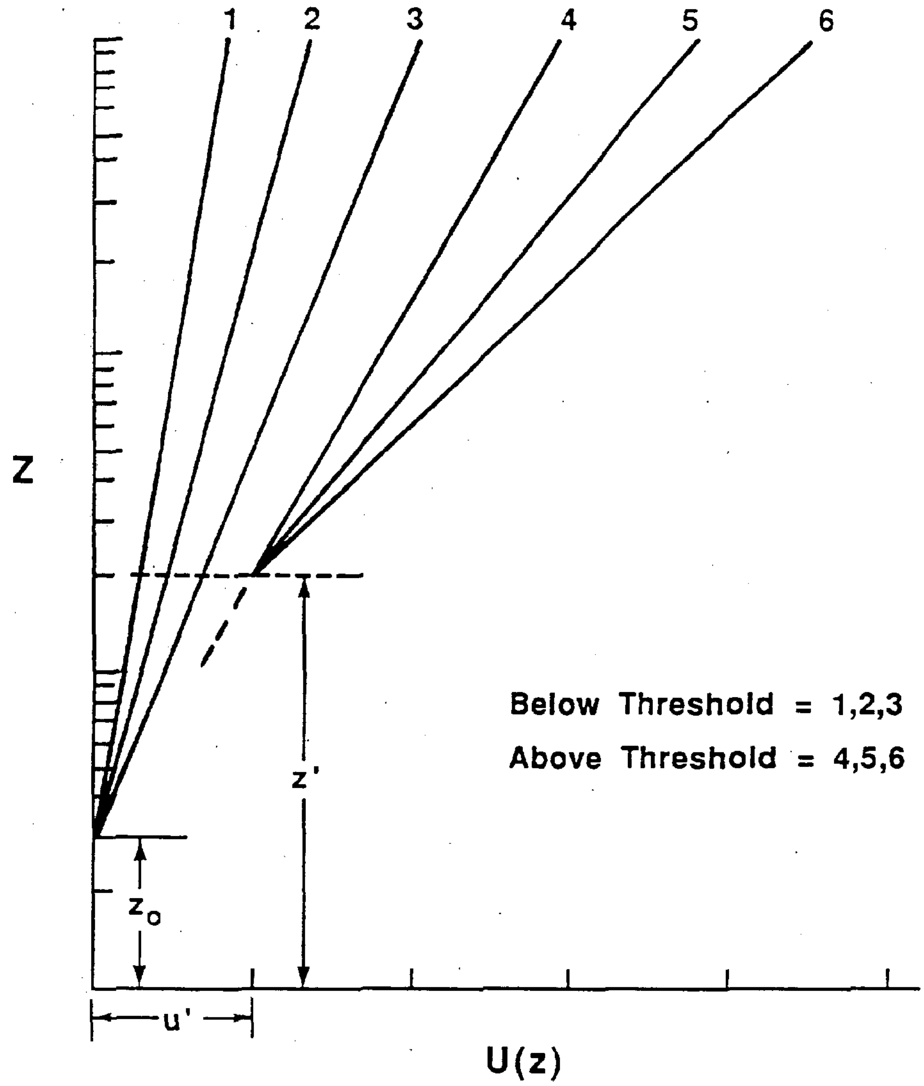

Figure 2 - Velocity profiles before and after the grain transport threshold is exceeded

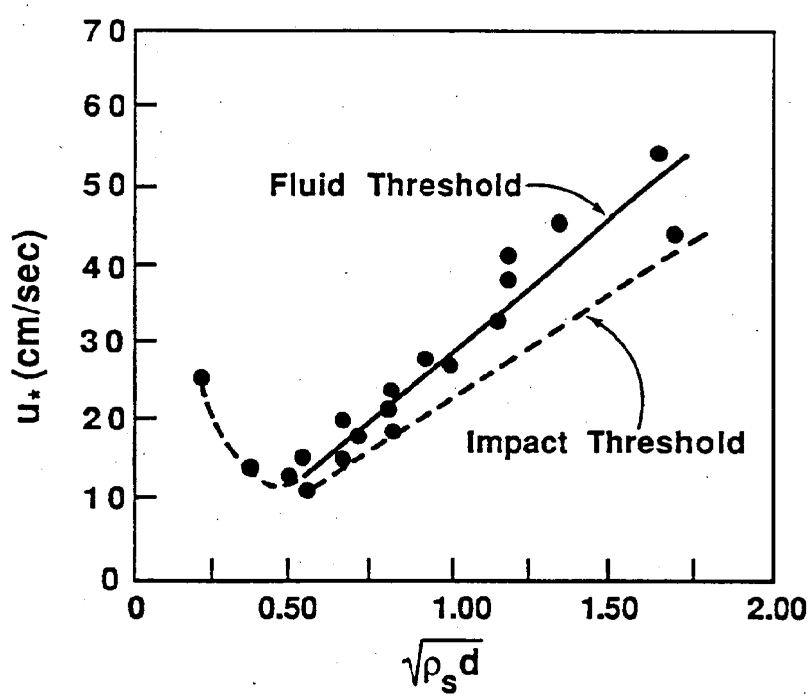

Figure 3 - Threshold shear velocities ($u_{*\,crit}$)

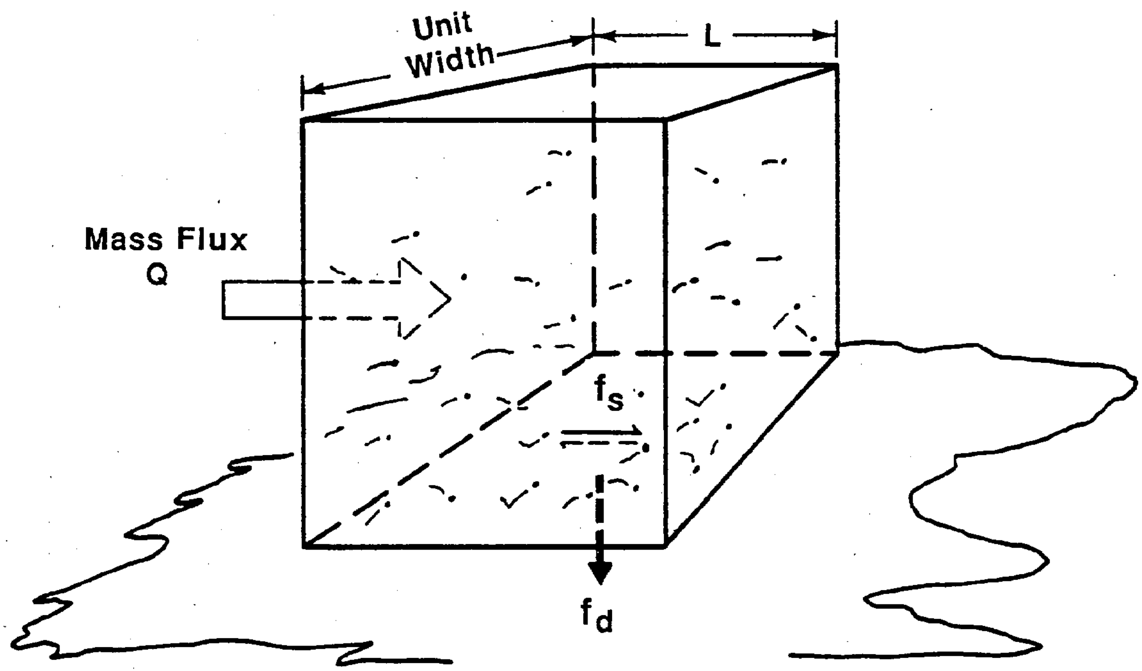

Figure 4 - Definition sketch of a sand transport control volume

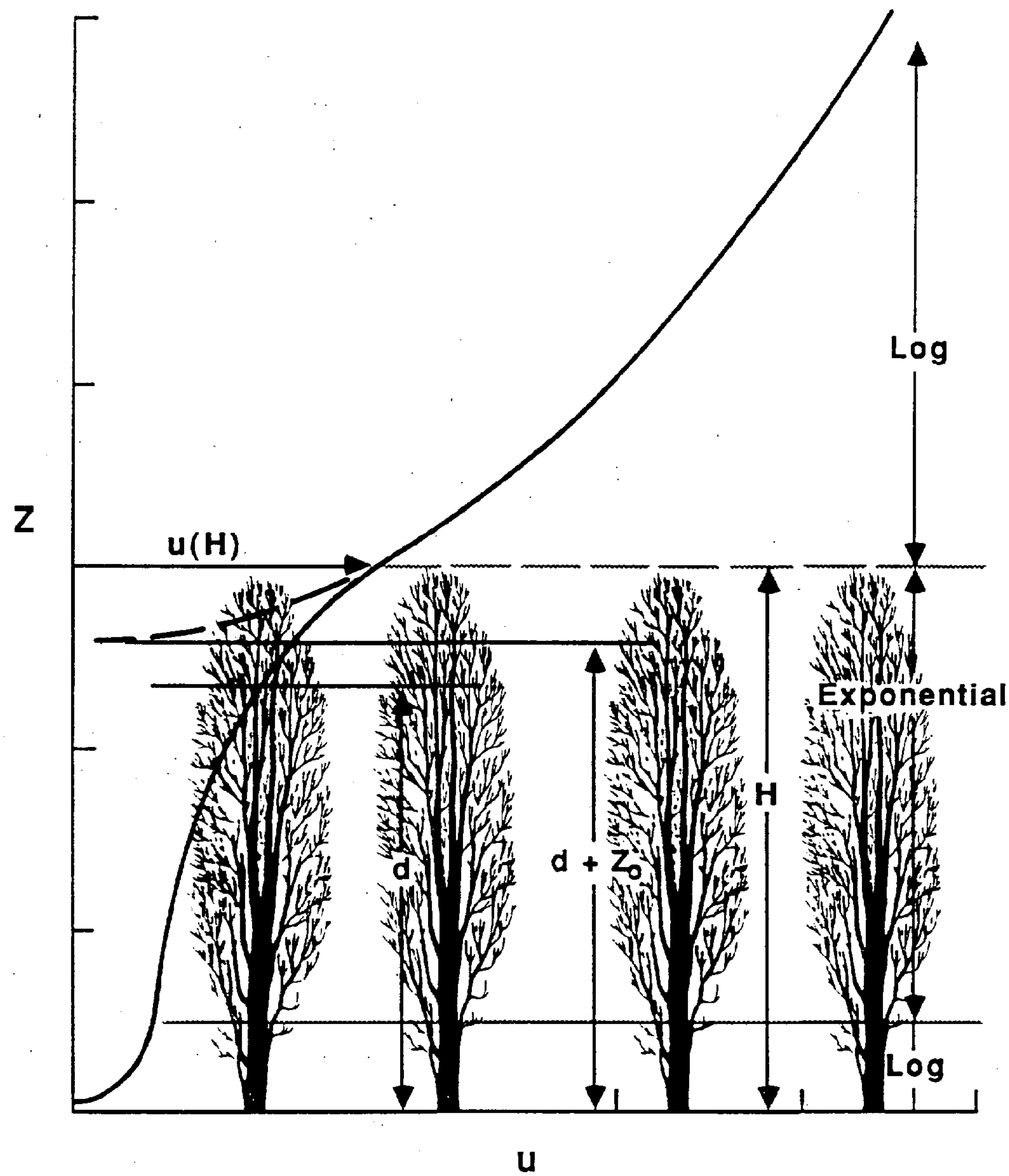

Figure 5 - Definition sketch of velocity profiles and a plant canopy

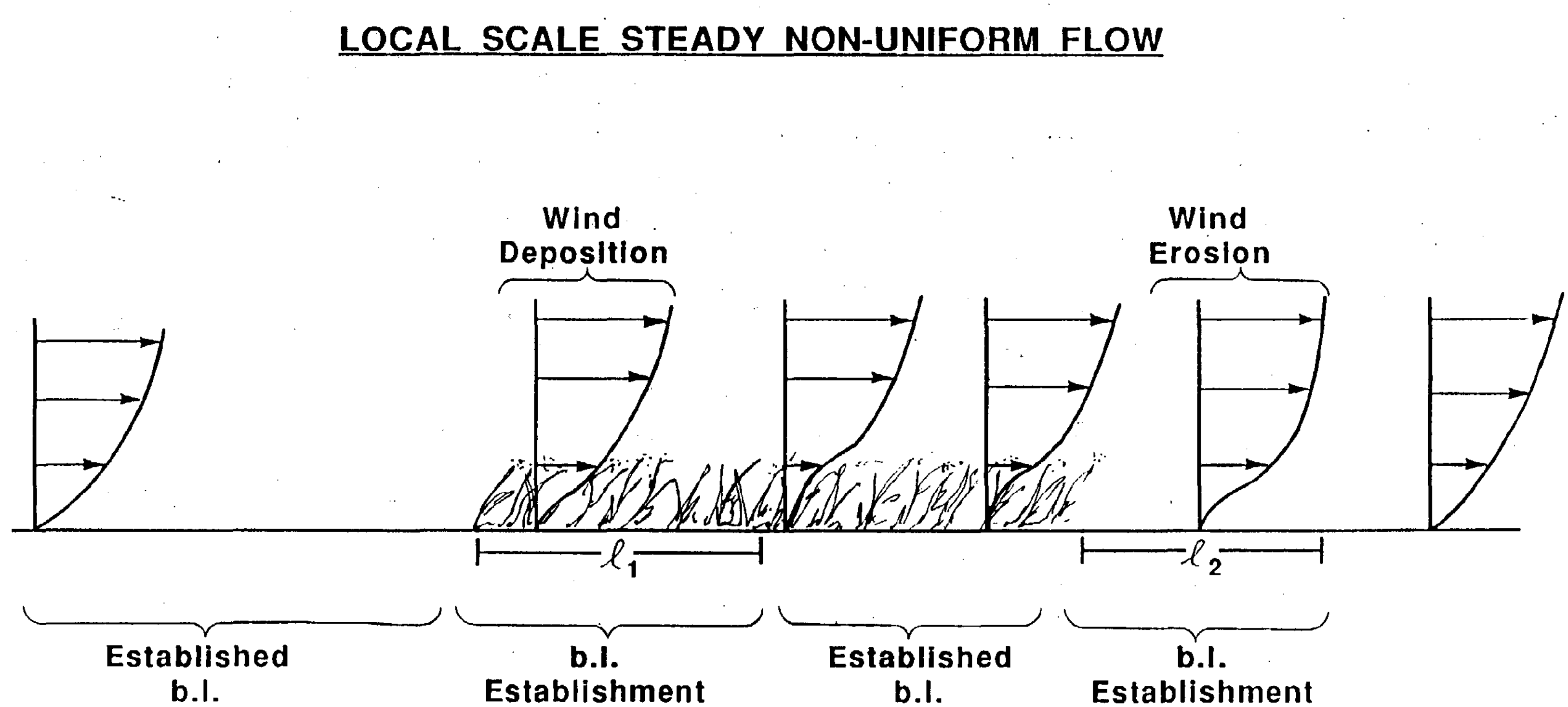

Figure 6 - Definition sketch of wind moving from bare sand to vegetation

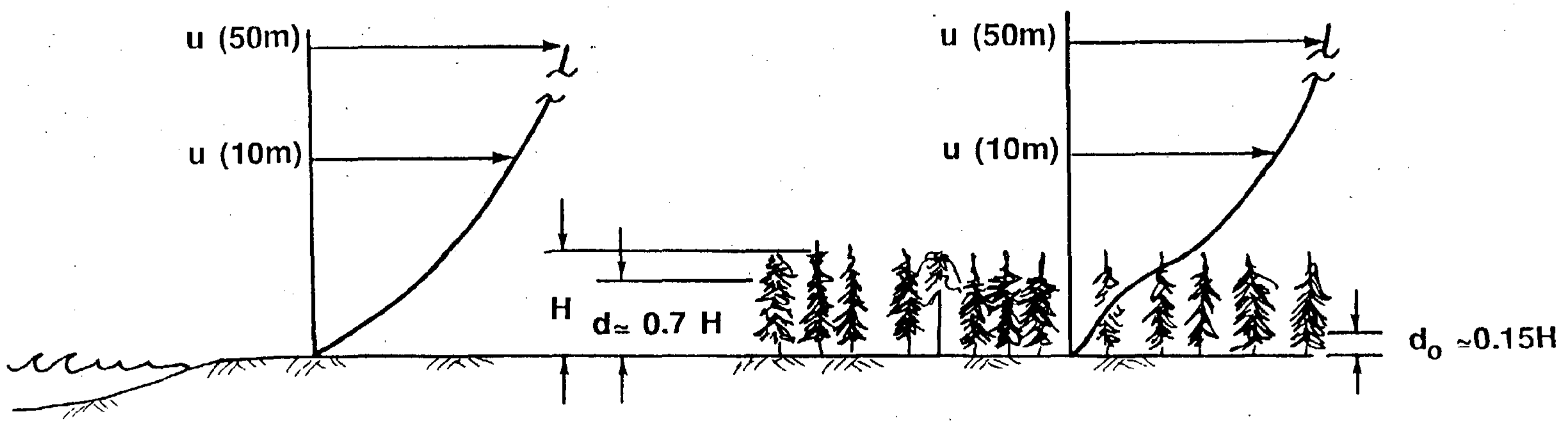

Figure 7 - Uniform flow analysis definition sketch

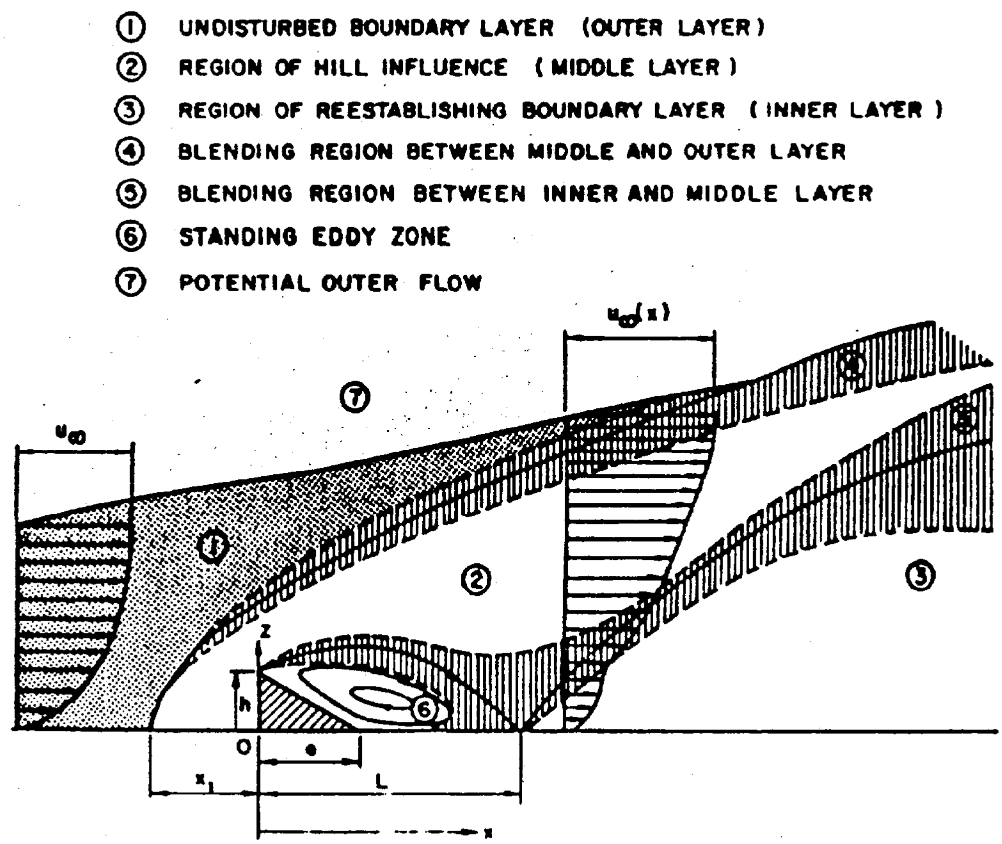

Figure 8 - Diagram of flow disturbances and boundary layer development around a non-porous barrier (from Plate 1971)

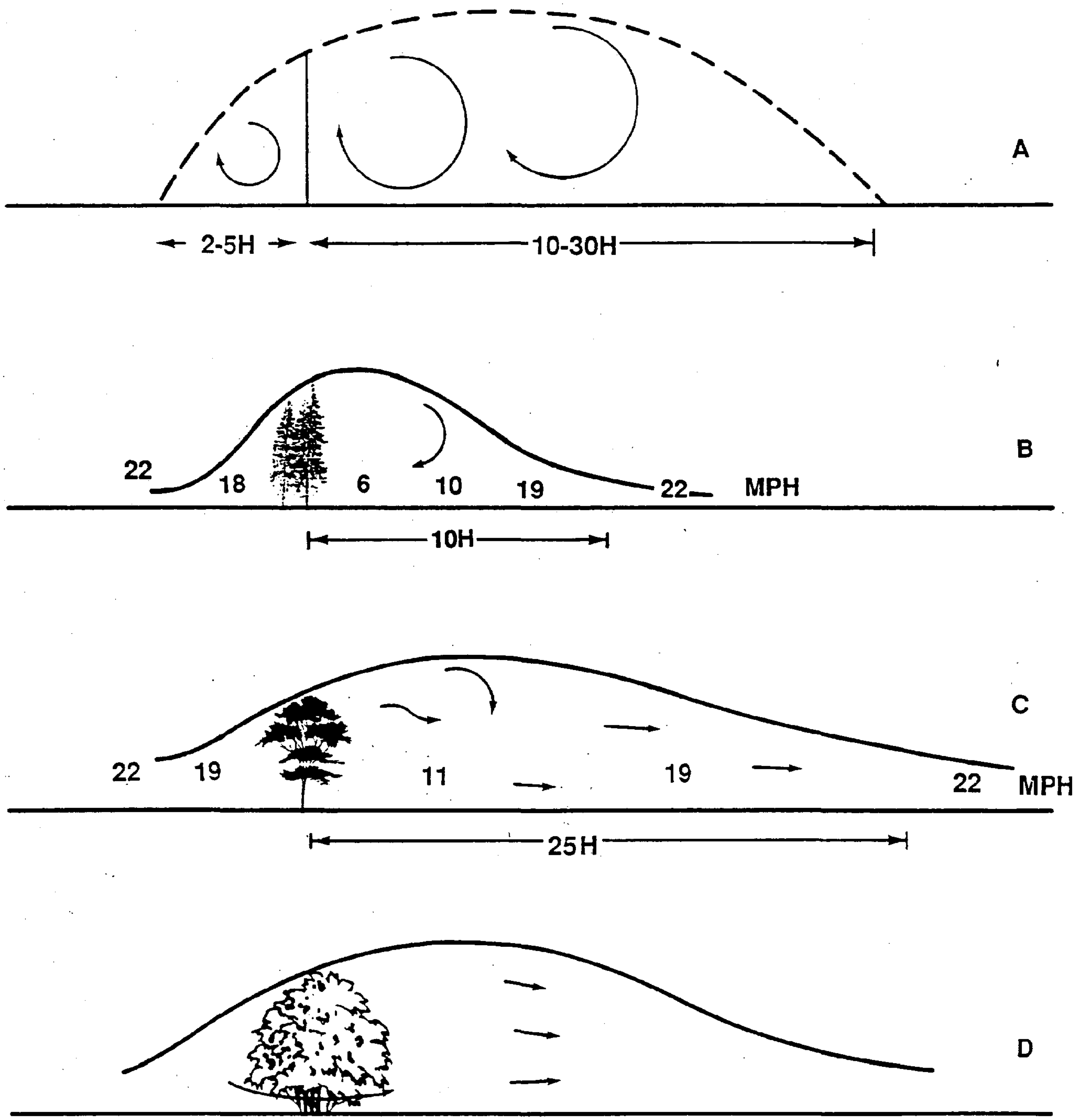

Figure 9 - Typical sheltering by vegetation strips. A: non-porous barrier, B: barrier with low porosity, C: barrier with moderate porosity, D: wind jetting under barrier foliage (from Robinette 1972)

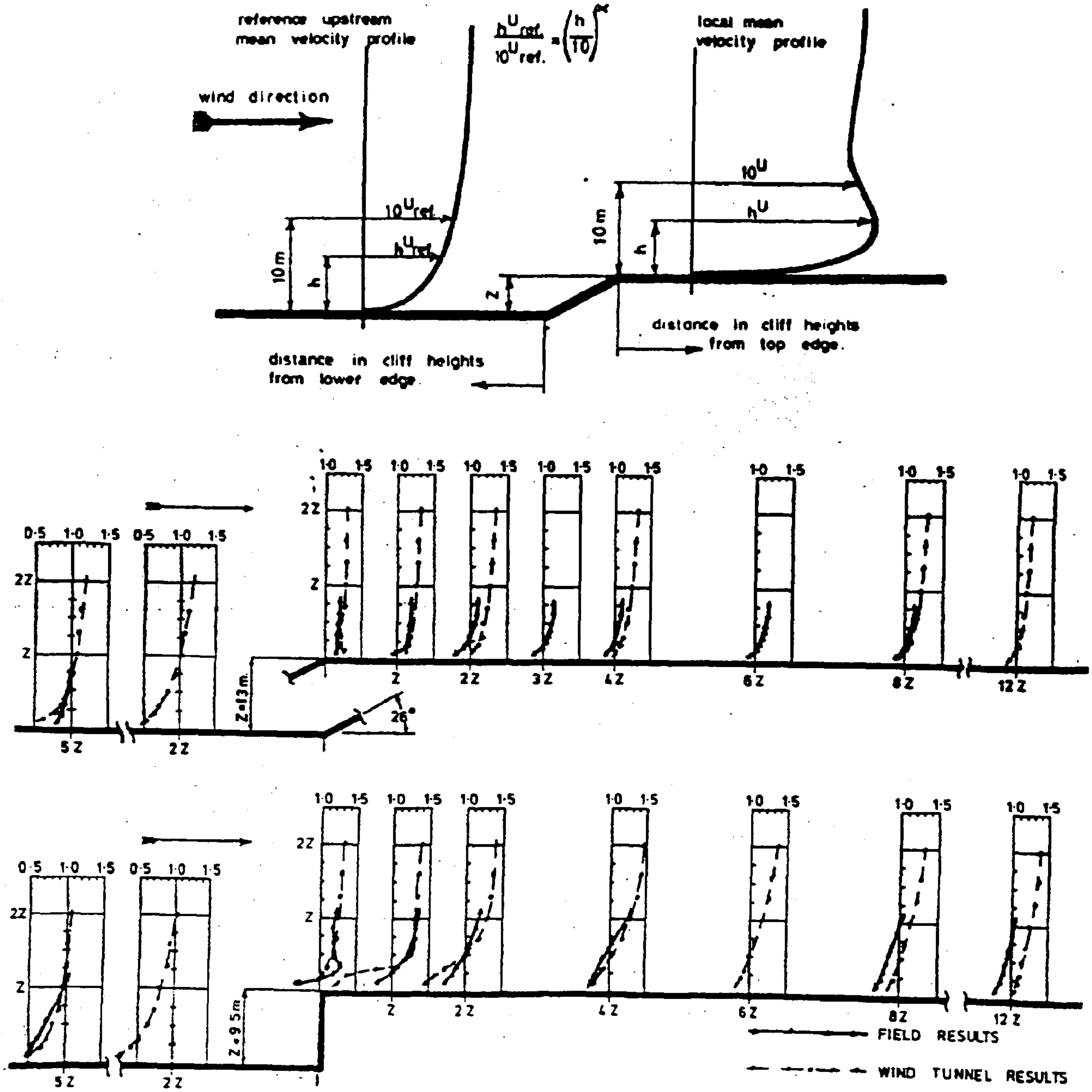

Figure 10 - Variation of mean wind speed over a sloping and cliff escarpment relative to the upstream wind speed at 10 m above the ground (from Bowen and Lindley 1974)

APPENDICES

Appendix A -- Vegetation Aerodynamic Parameters

Appendix A -- Vegetation Aerodynamic Parameters

The previous discussion of air flow through plant canopies shows that vegetation is effective in reducing the near-ground wind and consequently the associated sand transport. The present theories for predicting the effect of the vegetation canopy on the wind profile depend on aerodynamic parameters which must be measured for each plant type and community. These measurements must be performed carefully in the correct conditions to provide general results and therefore very few measurements are available in the literature. Furthermore, the understanding of the roles of many of the aerodynamic parameters in defining air flow was not recognized in the early stages of this research. Thus, several years went by with only incomplete data sets being produced, many with key parameters omitted.

The intent of this study is to understand the role of coastal vegetation in modifying the air flow and sand transport regime. The research on winds in plant canopies was motivated by agricultural and forestry concerns. Therefore, there are no direct measurements of the aerodynamic parameters for coastal vegetation typical of Florida. In order to provide a rational basis for analysing these questions before such measurements for coastal vegetation become available we have applied the concept of similitude, which is often used in problems of fluid flow, and estimated the aerodynamic parameters for the coastal plants based on the largest amount of measured data for non-coastal plants that could be assembled.

Although there have been several published attempts to relate some of the aerodynamic parameters to physical properties of the plants (or somewhat predictable flow scales such are the mixing length amid the foliage), none have proved successful. As a result, the estimates were based on judgement, guided by a good understanding of the underlying physics and assisted by the results of the numerical model developed by Shaw and Pereira (1982). Their results associate z_0/H and d/H with the product of the plant drag coefficient and the leaf area density as adjusted for the vertical distribution of foliage.

Table A-1 shows the total collection of measured data which were assembled. Almost all of the data are for crop plants or forest trees but some trees are the same as those found close to the beach in some places in Florida. Table A-2 lists the common dune plants of Florida and many of their physical characteristics. These characteristics were obtained for the literature where possible or estimated by experienced botanists. The physical characteristics such as typical plant height, diameter, spacing, leaf area, leaf area index, etc., and photographs where available, were used to assess the similarity of the unmeasured coastal plants to the plants with measured aerodynamic parameters. The assigned values of z_0/H, d/H, α, and the typical close spacing are shown on Table A-2.

A method was developed to provide for different spacing of the coastal vegetation in computing its effect on sand transport. Shaw and Pereira (1982) provide graphical results that relate z_0/H and d/H to the product of the leaf area density and the drag coefficient for the plant type. The leaf area density is easily adjusted for changes of the plant spacing and functions fit to the graphs were used to adjust z_0/H and d/H.

The modification of the exponential profile attenuation coefficient was accomplished in a similar way. Cionco (1978) provides the only published data. The attenuation coefficient is related to a planting density which is poorly defined. The data are available only for different planting densities of corn, in a set of field measurements and for different densities of wooden pegs, in a series of wind tunnel measurements. The data show similar trends to each other with the maximum attenuation occurring at about 1.5 times the closest spacing. At closer spacing the canopy is relatively impenetrable and the air flow tends to slide over the canopy as if it were a 'new' surface. Although these data are very limited they are the only source available and therefore were used as the basis of an equation which was fitted to the experimental results. This equation is used to adjust the attenuation coefficient for different plant spacings.

TABLE A-1 AERODYNAMIC PARAMETERS AND VEGETATION DATA

VEGETATION	PLANT TYPE	h (cm)	SPACING (cm)	Zo (cm)	D (cm)	Zo/h	D/h	ALPHA	Kc up	Kc canopy	Kc down	LAI	PAI (LAI/h)	SA	s (lot area) (HA)	SA/s	ROUGHNESS ELEMENT (cm)	DRAG COEF. Cd	DRAG COEF. C'd	Zmax/h	SOURCE	NOTES
corn	grass	50	40x40					1.6				0.56	0.012				5-10				Inoue & Uchijima (79)	* growing plants @ 59,000/HA
	grass	140	40x40					2				2.56	0.018				5-10					
	grass	225	40x40					2.6				4.2	0.019				5-10					
	grass	277	40x40					3				4.2	0.011				5-10					
	grass	225											2.9		25			0.17			Wilson, etal (82)	* total area index = total surf. area/unit ground area =
	grass																					* 59,000 plants/HA
	grass																					* 1695 sq. cm/plant
	grass	100-400															5-10				(various)	
	grass	280		0.75	253	0.003	0.90	2.09		0.21											Cionco (83)	
	grass	140		5	85	0.036	0.61	2.8													Uchijima & Wright (63)	* unpublished; from Inoue (63)
	grass											4.2									Cooper (75)	
	grass							0.06											0.22		Wilson & Shaw (77)	
grass	grass	30			20		0.67														Raynor (71)	
	grass	70			52		0.74														Fritschen, etal (85)	
Kochea	grass	20			10		0.50														Fritschen, etal (85)	
oats	grass	90		6.5	60	0.072	0.67	2.8		0.22											Cionco (83)	
	grass											4.2									Cooper (75)	
	grass	30-100															1.0				(various)	* leaf length = 25 cm
rice	grass											5									Tseng & Teng	* booting stage
	grass											4.5										* heading stage
	grass											3.6										* milk-ripe stage
	grass											3.2										* dough-ripe stage
	grass	85		6	50	0.071	0.59														Maitani (78)	* ear emergence stage
	grass	60		9.4	35	0.157	0.58															* young ear formation stage
	grass	122															1.0				(various)	* leaf length = 30 cm
	grass	76	20x20			0.000		2.45				3.65					1.0				Inoue & Uchijima (79)	* 240,000/HA in 30 cm rows; spacing 14x30 cm
	grass	85		25	50	0.294	0.59														Maitani (77)	
	grass	90		13	60	0.211	0.67	2.18		0.24											Nakagawa (56)	
	grass							1.62													Cionco (83)	
rush	grass	130		16	80	0.123	0.62														Maitani (78)	* harvest stage
sunflower	grass											1.89									Cox & Jolift (87)	* irrigated-early
	grass											4.5										* irrigated-late
	grass											1.27										* dryland-early
	grass											2.05										* dryland-late
	grass											5										* J. artichoke
	grass	198																			(various)	* leaf length = 5-18 cm
	grass	225		15.1	119	0.067	0.53	1.32		0.29											Cionco (83)	
wheat	grass	80		25	50	0.312	0.63														Maitani (78)	* ripening stage
	grass	100		8.8	60	0.088	0.60															* ripening stage
	grass	130		14.9	44	0.115	0.34	2.45		0.14											Cionco (83)	
	grass	122															1.0				(various)	* leaf length = 41 cm
	grass											3									Cooper (75)	
	grass	125	18	17.5	20	0.140	0.16	2.5					7		1				0.25		Legg (74)	* spacing is between rows
	grass																	0.2			Raines (71)	

TABLE A-1 AERODYNAMIC PARAMETERS AND VEGETATION DATA

VEGETATION	PLANT TYPE	h (cm)	SPACING (cm)	Zo (cm)	D (cm)	Zo/h	D/h	ALPHA	Rc up	Rc canopy	Rc down	LAI	PAI (LAI/h)	SA	s (lot area) (HA)	SA/s	ROUGHNESS ELEMENT (cm)	DRAG COEF. Cd	DRAG COEF. C'd	Zmax/h	SOURCE	NOTES
alfalfa "2a"	shrub	80			52	0.000	0.65														Fritschen, etal (85)	
alfalfa "a"	shrub	50			26	0.000	0.52															
bean	shrub	118		10.8	88.5	0.092	0.75						6.25						0.15		Thom (71)	
bean sprouts	shrub	100			60	0.000	0.60														Rider (56)	* all plants @ mature ht
cotton	shrub	132.3		13.8	50	0.104	0.38														Stanhill & Fuchs (67)	* mature plants
	shrub	126.9		12.6	62	0.099	0.49															
	shrub	47	25x80	14	45	0.298	0.96					1.1	3.4		0.01						Jarman (59)	* irrigated plants
	shrub	72	50x80	14	45	0.194	0.63					2.1	3		0.01							* 3 plants/hole
	shrub	80	50x80	14	45	0.175	0.56					3.8	4.6		0.01							* rows were 80 cm apart
	shrub	69	25x80	14	45	0.203	0.65					2.5	3.4		0.01							* not fully mature
	shrub	77	50x80	14	45	0.182	0.58					3.5	4.2		0.01							
	shrub	91	50x80	14	45	0.154	0.49					6.1	7		0.01							
Creosote bush	shrub	200			150	0.000	0.75														Fritschen, etal (85)	
peas	shrub	60			25	0.000	0.42														Rider (56)	
sagebrush	shrub	53	73x139	6.4	12.2	0.121	0.23										0.25				Hagen & Lyles (88)	
	shrub	68	73x139	5.4	54.4	0.079	0.80										0.25					
soybean	shrub	100		4.4	76	0.044	0.76	0.5		0.23											Cionco (83)	
	shrub											0.87									Cox & Joliff (87)	* irrigated-early
	shrub											6.8										* irrigated-late
	shrub											0.77										* dryland-early
	shrub											2.2										* dryland-late
	shrub	7.5-183																			(various)	* leaf length = 7.5-15 cm
	shrub																	0.12			Baldocchi (82)	* in Meyers & Paw (86)
yucca	shrub	44	73x218	5.3	7	0.120	0.16										2.0				Hagen & Lyles (88)	* d and Zo values are taken from figures showing these to be functions of PAI & Cd
	shrub	79	73x218	6.3	39.5	0.080	0.50															

VEGETATION	PLANT TYPE	h (cm)	SPACING (cm)	Zo (cm)	D (cm)	Zo/h	D/h	ALPHA	Rc up	Rc canopy	Rc down	LAI	PAI (LAI/h)	SA	s (lot area) (HA)	SA/s	ROUGHNESS ELEMENT (cm)	DRAG COEF. Cd	DRAG COEF. C'd	Zmax/h	SOURCE	NOTES
citrus	tree	360	730x610			0.000				0.49							2.54				Brooks & Shultz (55)	* distance between canopies 90 - 180 cm
citrus grove	tree											8.9									Hirano, etal (81)	* 13 yrs. old @ 10,000 trees/HA
	tree											7.6										* 5 yrs. old @ 10,000 trees/HA
	tree											4.7										* 13 yrs. old @ 1250 trees/HA
	tree											0.9										* 5 yrs. old @ 1250 trees/HA
	tree											7.1										* 1-3000 trees/HA; most common planting
	tree	370			221		0.60	0.44														
orange	tree	425	400x400	40.4	286	0.095	0.67					6.5			4.5				0.04	0.71	Kalma & Stanhill (71)	* trees 35 yrs. old
Douglas Fir	tree	2300-3000																			Hightshoe (78)	* leaf length = 2.5-4 cm; typical spread = 6-10 m
	tree	1550										9	0.006									* 60 yrs. old
	tree	70										7.7	0.11								Cooper (75)	* 5 yrs. old
	tree	1000										9	0.009									* 25 yrs. old
	tree	1420										9.31	0.007								Borghetti (85)	* plantation
fir	tree	3000			2100	0.000	0.70														Fritschen, etal (85)	
gum	tree	1500-2000															7.5				Hightshoe (78)	* leaf length = 7.5-15 cm; typical spread = 10-15 m
gum-maple	tree							4.4		0.07											Cionco (83)	
larch	tree	1040	300x300	57.1	809	0.055	0.78					9.36	0.013								Allen (68)	* 2/3 of needles dropped but rest well spaced
	tree			126.8	633																	* data for fully dropped needles ignored
	tree			81.3	750																	
	tree			39.2	784																	
	tree			206.7	494																	
	tree			52.2	733																	
	tree			112.4	635																	
	tree																					
	tree		ave =	96.8	691																	
	tree											4.1										
larch plantation	tree	1040		54	728	0.052	0.70	1		0.16											Cooper (75)	
	tree	1500-2300																			Hightshoe (78)	* leaf length = 1-4 cm
maple-fir	tree							4													Cionco (83)	
oak	tree	150										6.5	0.043								Cooper (75)	* sapling
	tree	1000										5.8	0.006									
	tree	2000-3200															1-5				Hightshoe (78)	* leaf length = 4-10 cm; typical spread = 15-23 m
oak-gum	tree							2.7		0.19											Cionco (83)	

TREES, continued...

TREES, continued...

TABLE A-1 AERODYNAMIC PARAMETERS AND VEGETATION DATA

VEGETATION	PLANT TYPE	h (cm)	SPACING (cm)	Zo (cm)	D (cm)	Zo/h	D/h	ALPHA	Rc up	Rc canopy	Rc down	LAI	PAI (LAI/h)	SA	s (lot area) (HA)	SA/s	ROUGHNESS ELEMENT (cm)	DRAG Cd	COEF. C'd	Zmax/h	SOURCE	NOTES
pine	tree	1050	120x150	100	800	0.095	0.76		0.68	0.15					6						Raynor (71)	# forest
	tree																					# 1474 trees/ha
	tree																					# trunk dist. @ breast ht. 3.8 - 35.3 cm
	tree																					# lowest living branches 2 - 4 m above ground
	tree																					# spacing is as planted in 1939
	tree												2.5						0.3		Halldin & Lindroth (85)	# projected needle area 2.5 (thin)
	tree	1850		128	1270	0.069	0.69														DeBruin (84)	
	tree	1850		139	1310	0.075	0.71														Molion & Moore (83)	
	tree	700			490	0.000	0.70														Fritschen, etal (85)	
	tree	700			460	0.000	0.66															
Red Pine	tree	2200			19.1	0.000	0.0087														Martin (71)	# density 60 - 70%
	tree	2200			19.3	0.000	0.0088															# bottom of canopy @ 10 m
	tree	2200			20.0	0.000																# forest
	tree	2200			19.9	0.000	0.0090															
	tree	2200			20.2	0.000	0.0092															
	tree	2200			19.8	0.000	0.0090															
	tree	2200			19.7	0.000	0.0090															
	tree	2200			20.2	0.000	0.0092															
	tree	2200			-------	0.000																
	tree	2200		ave. =	17.275		0.0079			0.23					12.1							
Scot Pine	tree									0.14											Cionco (83)	
Southern Pine	tree									0.2												
Red Maple	tree	2300-3000															5-10				Hightshoe (78)	# leaf length = 5-10 cm; typical spread = 15-22 m
	tree	1300										5.13	0.004								Wang & Miller (87)	# 30 yrs. old
Saltcedar	tree	200			150	0.000	0.75														Fritschen, etal (85)	
	tree	600			350	0.000	0.58															
spruce	tree											9.7									Cooper (75)	# 25 yrs. old
	tree											10.6										# 60 yrs. old
	tree	1500-3000															0.5				Hightshoe (78)	# leaf length = 1-2 cm; typical spread = 6-10 m
	tree							2.7		0.13											Cionco (83)	
	tree	1050		136.5	672	0.130	0.64	1.8				10							0.14		Landsberg & James (71)	

TABLE A-2 COASTAL VEGETATION AERODYNAMIC PARAMETERS

VEGETATION	PLANT TYPE	h (cm)	SPACING (cm)	Zo/h	D/h	ALPHA	LAI	PAI (LAI/h)	SA	s (lot area) (sq. cm)	SA/s	LEAF LENGTH (cm)	LEAF AREA (sq. cm)	PLANT DIA. (cm)	FLEXIBILITY	HARDINESS	SIMILAR PLANT	NOTES
Dune Prairie Grass	grass	150	46	0.040	0.60	2.4	4.60	0.031	3010	2090	1.440	137	250	25.3	high	high	corn	* corn values used
Saltmeadow Cordgrass	grass	90	12.2	0.125	0.60	2.2	5.00	0.056	372	149	2.497	61	37	12.2	high	high	rice	* rice values used
Sea Oats	grass	183	60	0.120	0.60	2.5	4.00	0.022	560	1860	0.301	60	46	15	high	high	wheat	* wheat values used
Beach Bean	herb	15	122	0.070	0.50	1.3	2.84	0.256	620	14860	0.042	7.6	37	15	mod	high	squash	* sunflower values used
Beach Croton	herb	70	60	0.120	0.56	0.5	1.68	0.024	117	3750	0.031	5.2	13	15	mod	mod	bushel baskets	* shrub default values used
Beach Morning Glory	herb	15	27	0.070	0.53	1.3	4.32	0.288	1630	752	2.168	10	65	6.1	mod	high	watermelon	* sunflower values used
Dune Sunflower	herb	90	76	0.070	0.53	1.3	1.60	0.018	2930	5850	0.501	7.6	59	60	mod	high	watermelon	* sunflower values used
Railroad Vine	herb	15	21	0.070	0.50	1.3	4.90	0.327	1115	460	2.424	10	74	7.6	mod	high	watermelon	* sunflower values used
Sea Blite	herb	76	61	0.120	0.56	0.5	2.40	0.032	557	3720	0.150	5.2	2.8	15	low	mod	wooden pegs	* shrub default values used
Sea Purslane	herb	15	30	0.120	0.56	0.5	1.20	0.080	280	940	0.298	3.8	2.8	15	mod	high	wooden pegs	* shrub default values used
Camphorweed	shrub	70	90	0.125	0.56	0.5	1.25	0.018	500	8430	0.059	5.2	8.4	37	mod	high	soybean	* shrub default values used
Cocoplum	shrub	300	460	0.060	0.80	1.5	10.00	0.033	93000	186000	0.500	5.1	193	460	low	high	jungle	* poor comparison-adjustments made to default values
Conradina	shrub	90	150	0.125	0.56	0.5	1.20	0.013	2443	23200	0.105	1.2	0.93	60	mod	mod		* default shrub values used
Gray Nickar Bean	shrub	150		0.125	0.56	0.5	7.10	0.047	111500			5.2	13	460	mod	high	citrus	* poor comparison--shrub default values used
Prickly Pear Cactus	shrub	90	30	0.120	0.50	0.4	2.40	0.027	2150	930	2.312	21	1430	24	low	high	bushel baskets	* erect plants with firm, flat paddle-shaped leaves
Rosemary	shrub	90	180	0.125	0.56	0.5	1.20		3500	33400	0.105	1.2	3.7	76	mod	low	plastic strips	* poor comparison--shrub default values used
Saw Palmetto	shrub	150	15	0.120	0.50	0.6	4.20	0.028	17400	23400	0.744	76	5800	90	mod	high	bushel baskets	* comparison based on yucca and cotton/alfalfa
Sea Grape	shrub	240	240	0.100	0.70	1.5	10.00	0.042	93000	186000	0.500	20	410	244	low	high	jungle	* spreads hor.; much wind shear across surf; comp. data, med
Sea Myrtle	shrub	200	150	0.125	0.56	0.5	3.60		16900	23200	0.728	3.8	9.3	107	mod	high	sunflower	* medium level of comparable data
Spanish Bayonet	shrub	215	300	0.100	0.50	1.0	3.20	0.015	13500	93650	0.144	52	269	90	low	high	yucca	* good comparison with yucca data
Australian pine	tree	3000	600	0.090	0.70	2.7	23.60		836000	371600	2.250	21		900	low	high	spruce	* d/H and Zo/H reasonable comparison; alpha, poor
Bay Cedar	tree	2400	150	0.120	0.64	2.5	10.60	0.004	37200	23200	1.603	3.8	3.7	150	low	mod	spruce	* values for spruce used
Cabbage Palm	tree	2300	600	0.070	0.50	1.3	7.10		146300	371600	0.394	75		460	low	high	oak	* values for sunflower used
Chapman's Oak	tree	600	180	0.060	0.70	2.7	15.10		66900	33400	2.003	7.6	12	183	low	high	oak	* grows w/Myrtle Oak; dense thickets; values like Live Oak
Coconut Palm	tree	900	750	0.070	0.50	1.3	12.60		418000	580600	0.720	460		900	mod	mod		* values for sunflower used
Myrtle Oak	tree	300	120	0.100	0.70	2.0	9.80	0.033	37200	19500	1.908	7.6	12	152	low	high	oak	* dense thickets; spacing smaller than plant dia; poor comp.
Sand Live Oak	tree	900	460	0.060	0.70	2.7	18.90		445900	209000	2.133	5.2	13	600	low	high	oak	* poor data
Sand Pine	tree	900	460	0.090	0.70	2.5	12.60		334400	210700	1.587	7.6		900	low	high	pine	* d/H and Zo/H reasonable data;alpha, poor
Slash Pine	tree	1830	900	0.090	0.70	2.5	18.80		891800	836000	1.067	25		120	low	high	spruce	* d/H and Zo/H reasonable data;alpha, poor
Southern Magnolia	tree	180	900	0.09	0.60	1.5	14.10		1170500	836000	1.400	15		900	low	high	gum	* not often in coastal situations; only in panhandle
Southern Red Cedar	tree	760	600	0.07	0.70	2.7	15.70		464500	371600	1.250	6		600	low	high	christmas tree	* pine, Salt Cedar, and larch values used
Wax Myrtle	tree	520	280	0.11	0.60	1.0	3.50	0.007	79000	75240	1.050	10	21	213	low	high	oak	

Appendix B -- Recommendations for Future Work

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There are clearly two major areas of future work that are essential to the successful application of the results of this study to the permit review procedures of the Division of Beaches and Shores. One is to develop and experimental program, including both field and wind tunnel measurements to verify and extend the methods which have so far been entirely based on literature values and relationships.

The other major need is to extend this work to the coastal scale so that the larger scale effects of changes in coastal vegetation can be identified and quantified. It was not possible to accomplish this until there was a proper understanding of the role of coastal vegetation on the local scale and the results of this study largely provide this. Much of this work can be acomplished with properly selected numerical models, supported by a carefully designed field effort to verify and calibrate the models.

Appendix C -- Comprehensive Bibliography

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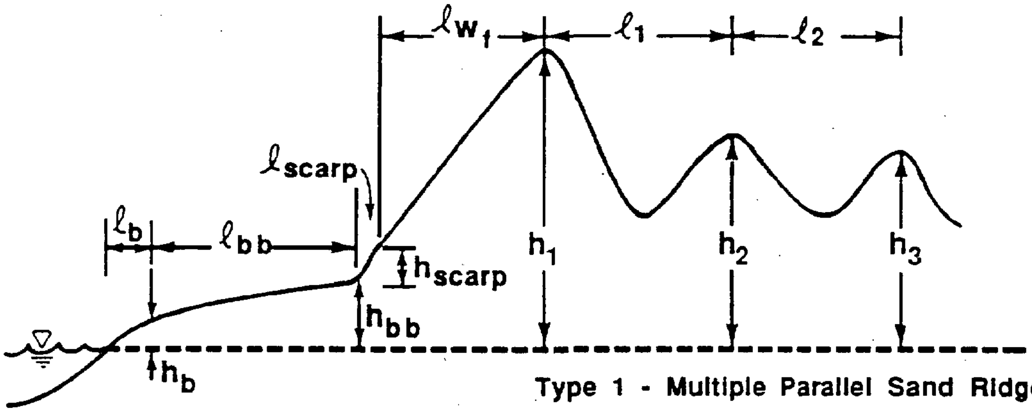
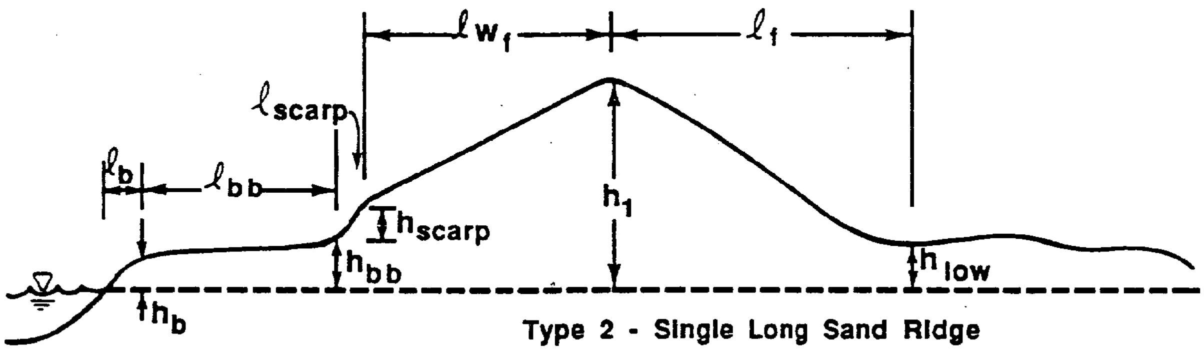
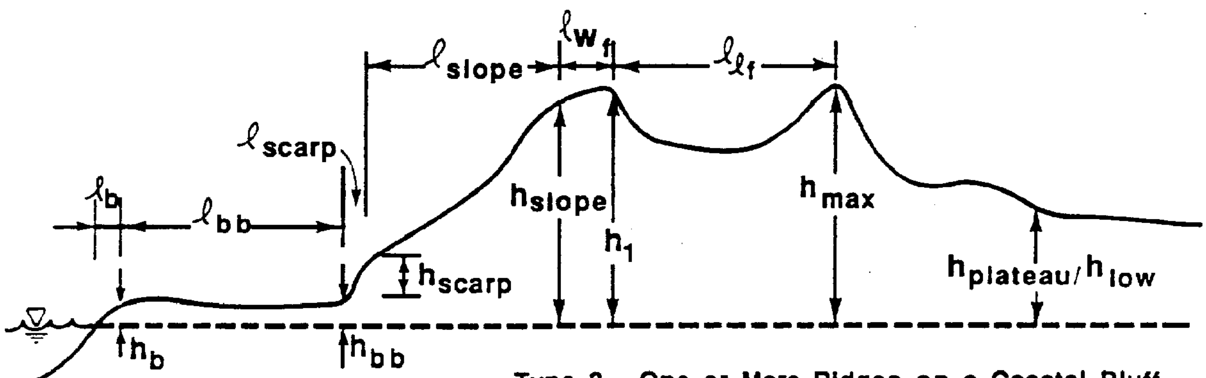
Appendix D -- Dune Forms of Florida Coast



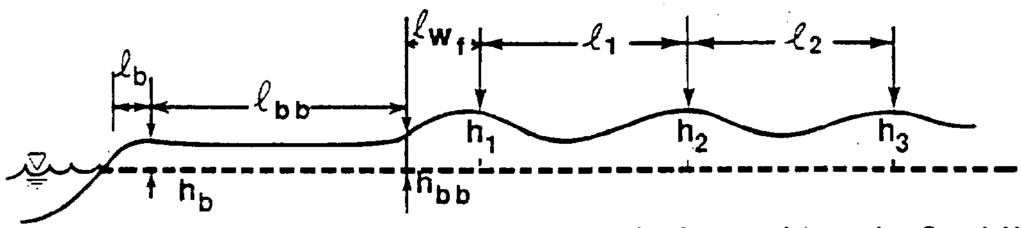
Type 1 - Multiple Parallel Sand Ridges



Type 2 - Single Long Sand Ridge



Type 3 - One or More Ridges on a Coastal Bluff



Type 4 - Low and Irregular Sand Hills

FLORIDA COASTAL DUNE PARAMETERS

FLAGLER (CLASS=2)

	l_b	h_b	l_{bb}	h_{bb}	l_{sc}	h_{sc}	l_{wf}	l_{lf}	l_1	l_2	h_1	h_2	h_3	l_{s1}	h_{s1}	h_{max}	h_{low}
R-7	50	2	0	0	0	0	80	240	0	0	16	0	0	0	0	0	7.5
R-14	50	5	50	10	0	0	20	208	0	0	12	0	0	0	0	0	2.5
R-16	100	7	45	12	0	0	8	256	0	0	14	0	0	0	0	0	5.0
R-22	48	5	55	11.5	0	0	10	208	0	0	16	0	0	0	0	0	7.0
R-47	50	1	50	3.5	50	6.5	48	176	0	0	25	0	0	0	0	0	8.0
R-48	50	1.5	50	5.5	32	4.5	48	82	0	0	23.5	0	0	0	0	0	9.0
R-55	50	3	50	5	50	3	80	72	0	0	26	0	0	0	0	0	20

FLAGLER (CLASS=3)

	l_b	h_b	l_{bb}	h_{bb}	l_{sc}	h_{sc}	l_{wf}	l_{lf}	l_1	l_2	h_1	h_2	h_3	l_{s1}	h_{s1}	h_{max}	h_{low}
R-65	100	9	50	12	16	7	20	52	0	0	24	0	0	16	21.5	20.5	19
R-67	72	7	80	10	0	0	32	44	0	0	24	0	0	0	0	23	18
R-80	50	2	50	3	50	2	24	96	0	0	20.5	0	0	50	9	20	19
R-82	50	3.5	50	10	32	2.5	16	88	0	0	21.5	0	0	0	0	21.5	19
R-91	50	2.5	50	9	56	2.5	16	176	0	0	27	0	0	32	18	27	26
R-97	50	5.2	40	10.5	24	2	20	65	0	0	21.5	0	0	16	17	22.5	19
R-98	72	9	30	9.5	24	28	16	24	0	0	22	0	0	12	15	22	20

FLORIDA COASTAL DUNE PARAMETERS (CONTINUED)

ST. LUCIE (CLASS=1)

	l_b	h_b	l_{bb}	h_{bb}	l_{sc}	h_{sc}	l_{wf}	l_{lf}	l_1	l_2	h_1	h_2	h_3	l_{s1}	h_{s1}	h_{max}	h_{low}
R-15	50	4.8	50	11.5	0	0	16	0	40	40	14.5	13.5	14.5	0	0	0	0
R-16	50	5	48	10	0	0	20	0	68	40	12	14	11.5	0	0	0	0
R-19	24	1.6	56	8	32	4.4	12	0	52	24	14	12.8	13.6	0	0	0	0
R-21	48	4.5	0	0	0	0	72	0	96	96	12.5	12.4	14	0	0	0	0
R-31	48	3.5	50	8	28	2.5	40	0	52	80	14	10.8	11.2	0	0	0	0
R-32	100	7.2	32	8.8	16	0.4	48	0	104	64	15.5	10	15.5	0	0	0	0
R-35	48	5.6	24	8.8	0	0	40	0	152	124	11	7.2	7.2	0	0	0	0

ST. LUCIE (CLASS=2)

	l_b	h_b	l_{bb}	h_{bb}	l_{sc}	h_{sc}	l_{wf}	l_{lf}	l_1	l_2	h_1	h_2	h_3	l_{s1}	h_{s1}	h_{max}	h_{low}
R-58	32	2	55	8.4	0	0	32	225	0	0	15.4	0	0	0	0	0	4
R-59	50	3.2	50	10	0	0	8	240	0	0	11.2	0	0	0	0	0	4.8
R-60	50	2.4	0	0	0	0	80	192	0	0	11.2	0	0	0	0	0	3.2
R-70	40	4.5	40	11.2	0	0	8	274	0	0	12.4	0	0	0	0	0	2.8
R-75	50	4	50	9.2	12	3.2	10	208	0	0	15.0	0	0	0	0	0	3.6
R-86	40	3.2	56	9.6	0	0	36	152	0	0	10.0	0	0	0	0	0	4.5
R-99	0	0	0	0	0	0	100	100	0	0	13.2	0	0	0	0	0	8

FLORIDA COASTAL DUNE PARAMETERS (CONTINUED)

NASSAU (CLASS=1)

	l_b	h_b	l_{bb}	h_{bb}	l_{sc}	h_{sc}	l_{wf}	l_{lf}	l_1	l_2	h_1	h_2	h_3	l_{s1}	h_{s1}	h_{max}	h_{low}
R-33	50	2	45	3.5	155	8.5	25	0	75	25	16.5	20.5	23	0	0	0	0
R-36	50	4	50	3.5	50	1	150	0	100	17	17	20.5	22	0	0	0	0
R-42	50	1	40	1.5	110	2	90	0	35	50	15.5	16	13.5	0	0	0	0
R-46	50	1.5	100	3.5	50	2.5	65	0	62	58	16	17.5	14.5	0	0	0	0
R-53	100	4	100	6	45	2.5	60	0	85	85	19.5	16.5	24	0	0	0	0
R-63	100	1	50	3	110	4.5	55	0	45	75	16	20.5	26.5	0	0	0	0
R-73	50	2	50	2.5	50	1	65	0	80	230	8.5	17.5	26.5	0	0	0	0

NASSAU (CLASS=2)

	l_b	h_b	l_{bb}	h_{bb}	l_{sc}	h_{sc}	l_{wf}	l_{lf}	l_1	l_2	h_1	h_2	h_3	l_{s1}	h_{s1}	h_{max}	h_{low}
R-10	100	3.5	65	7.5	35	2	140	110	0	0	21	0	0	0	0	0	8.5
R-11	50	2	50	3.5	40	5	160	65	0	0	16.5	0	0	0	0	0	10.5
R-12	50	1.5	25	2	25	2	85	80	0	0	9.5	0	0	0	0	0	8.5
R-17	50	2	60	7	50	3	55	75	0	0	14	0	0	0	0	0	9.5
R-18	50	2.5	48	7	25	1.5	150	125	0	0	14	0	0	0	0	0	9.5
R-19	80	5	36	5	40	3.5	90	115	0	0	11.5	0	0	0	0	0	13.5
R-20	50	2	50	3.5	50	3	30	90	0	0	11.5	0	0	0	0	0	9.5

MANATEE (CLASS=2)

l_b	h_b	l_{bb}	h_{bb}	l_{sc}	h_{sc}	l_{wf}	l_{1f}	l_1	l_2	h_1	h_2	h_3	l_{s1}	h_{s1}	h_{max}	h_{low}	
50	2	30	6	20	1	90	100	0	0	11	0	0	0	0	0	7	R-57
25	4	0	0	15	2	80	42	0	0	8.5	0	0	0	0	0	7.5	R-58
10	2	44	6	20	2.5	50	90	0	0	10.5	0	0	0	0	0	10	R-59
25	2	30	4	20	2	48	28	0	0	12	0	0	0	0	0	10.5	R-63
50	3.5	0	0	20	1	18	80	0	0	10	0	0	0	0	0	8	R-64
82	7.5	0	0	0	0	17	60	0	0	11	0	0	0	0	0	9	R-65
25	2	0	0	0	0	25	150	0	0	11	0	0	0	0	0	8.5	R-67

MANATEE (CLASS=4)

l_b	h_b	l_{bb}	h_{bb}	l_{sc}	h_{sc}	l_{wf}	l_{1f}	l_1	l_2	h_1	h_2	h_3	l_{s1}	h_{s1}	h_{max}	h_{low}	
5	2	25	4	0	0	150	0	1.25	94	6	9	8	0	0	0	0	R-3
50	4.5	16	4	0	0	40	0	175	115	4.5	9.5	6	0	0	0	0	R-4
25	2.5	25	4	0	0	65	0	60	65	10	10.5	7.5	0	0	0	0	R-5
35	2	15	2	0	0	30	0	25	100	5	5.5	8.5	0	0	0	0	R-36
80	4	20	3	0	0	110	0	65	88	12	10	8	0	0	0	0	R-41
55	4	225	4.5	0	0	40	0	155	0	12.5	2.5	0	0	0	0	0	R-44
50	5	30	6.5	0	0	48	0	150	120	7.5	7.5	8	0	0	0	0	R-52

CHARLOTTE (CLASS=1)

l_b	h_b	l_{bb}	h_{bb}	l_{sc}	h_{sc}	l_{wf}	l_{1f}	l_1	l_2	h_1	h_2	h_3	l_{s1}	h_{s1}	h_{max}	h_{low}	
24	2	32	4.5	16	0.8	16	0	168	200	7.2	6.4	4.8	0	0	0	0	R-49
20	2.5	32	4.8	16	1	40	0	88	160	8	9.6	4.4	0	0	0	0	R-50
0	0	0	0	0	0	64	0	120	80	5.2	6.6	7.2	0	0	0	0	R-51
25	2.8	50	3.6	32	6	28	0	104	36	6	7.2	7	0	0	0	0	R-53
24	2.4	20	3.6	0	0	80	0	85	32	6	8.4	10	0	0	0	0	R-54
16	0.4	36	4	112	2.4	16	0	164	72	10.8	2.4	2.6	0	0	0	0	R-55

FLORIDA COASTAL DUNE PARAMETERS (CONTINUED)

CHARLOTTE (CLASS=2)

l_b	h_b	l_{bb}	h_{bb}	l_{sc}	h_{sc}	l_{wf}	l_{lf}	l_1	l_2	h_1	h_2	h_3	l_{sl}	h_{sl}	h_{max}	h_{low}	
0	0	0	0	0	0	40	36	0	0	4.4	0	0	0	0	0	3.2	R-32
48	6	36	5.6	32	1.2	12	248	0	0	8.4	0	0	0	0	0	3.6	R-35
50	7.2	36	4.8	36	2	44	80	0	0	9.2	0	0	0	0	0	6	R-36
40	3.2	32	4.8	20	1	24	88	0	0	7.2	0	0	0	0	0	5.8	R-39
44	3.2	28	5	32	1.6	28	260	0	0	8.4	0	0	0	0	0	2	R-40
24	2.8	36	4	32	2	24	96	0	0	8.4	0	0	0	0	0	5	R-41
48	4.8	40	3.6	20	0.8	0	164	0	0	4.8	0	0	0	0	0	2	R-47

CHARLOTTE (CLASS=4)

l_b	h_b	l_{bb}	h_{bb}	l_{sc}	h_{sc}	l_{wf}	l_{lf}	l_1	l_2	h_1	h_2	h_3	l_{sl}	h_{sl}	h_{max}	h_{low}	
50	4.4	50	4.4	0	0	36	0	240	0	9	7.6	0	0	0	0	0	R-6
48	4	64	4.2	0	0	96	0	160	116	11	6	6	0	0	0	0	R-7
44	4.8	64	4.8	0	0	80	0	152	96	11.2	10	4.6	0	0	0	0	R-8
32	4	44	3.6	0	0	84	0	120	100	8.8	5.6	6.8	0	0	0	0	R-11
16	3	64	8	0	0	52	0	32	52	11.6	11.6	11.2	0	0	0	0	R-12
16	1.2	0	0	0	0	24	0	128	196	4	8.6	5.6	0	0	0	0	R-27
8	1.4	32	5.6	0	0	52	0	100	160	6.4	11	6	0	0	0	0	R-29

WALTON (CLASS=1)

l_b	h_b	l_{bb}	h_{bb}	l_{sc}	h_{sc}	l_{wf}	l_{lf}	l_1	l_2	h_1	h_2	h_3	l_{sl}	h_{sl}	h_{max}	h_{low}	
60	6	82	9	25	4.5	42	0	75	100	23.5	26.5	25.5	0	0	0	0	R-35
0	0	0	0	0	0	45	0	140	50	6	8.5	8	0	0	0	0	R-46
30	5	20	3.5	100	5	50	0	150	250	25.5	11.5	13	0	0	0	0	R-53
30	3	20	0.5	0	0	30	0	180	75	5.5	8.5	12.5	0	0	0	0	R-69
12.5	2	25	5	0	0	48	0	165	110	8	19	13	0	0	0	0	R-70
0	0	0	0	0	0	60	0	135	100	7	7.5	8.5	0	0	0	0	R-72
0	0	0	0	0	0	42	0	155	100	5	14	24	0	0	0	0	R-103

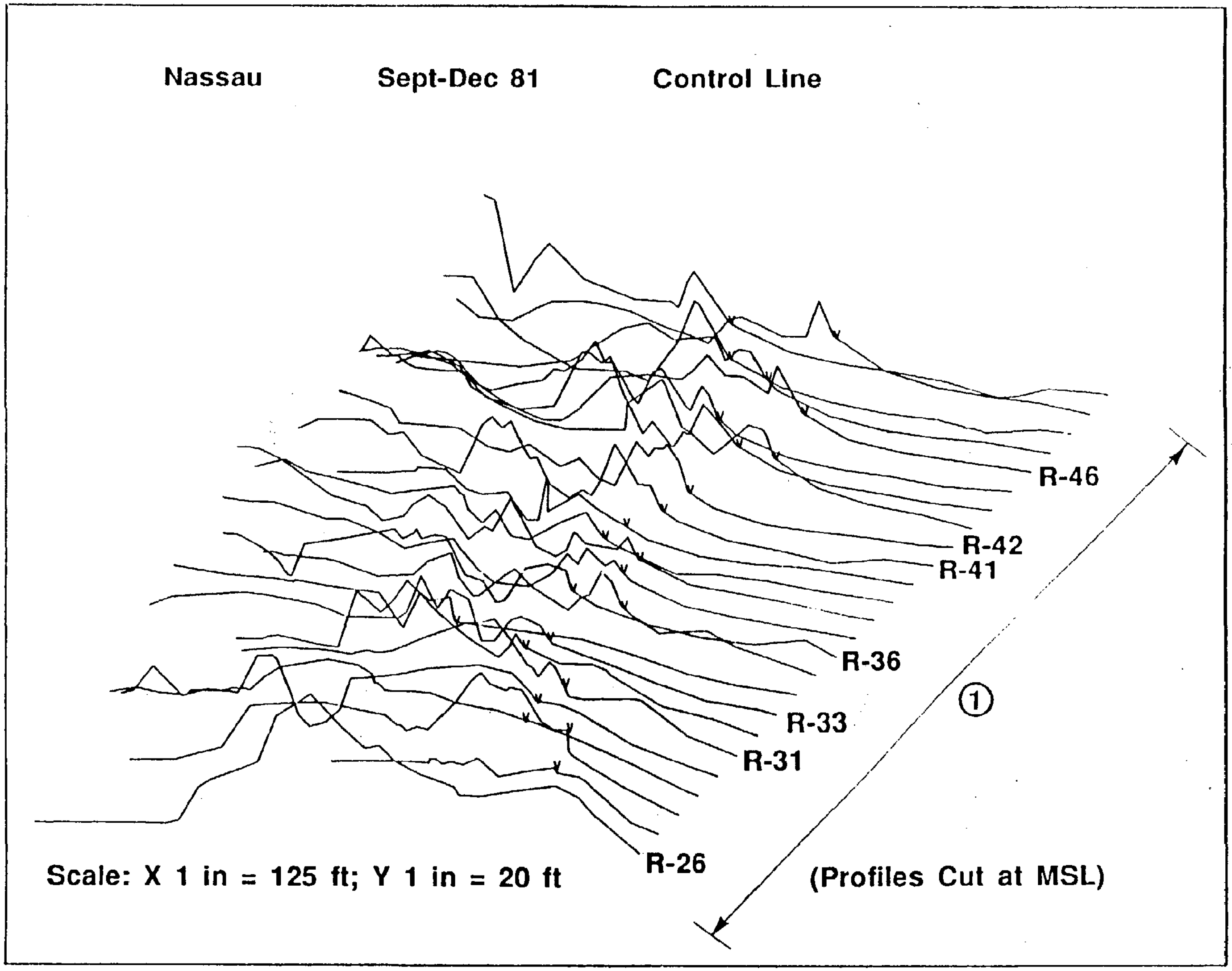
FLORIDA COASTAL DUNE PARAMETERS (CONTINUED)

WALTON (CLASS=2)

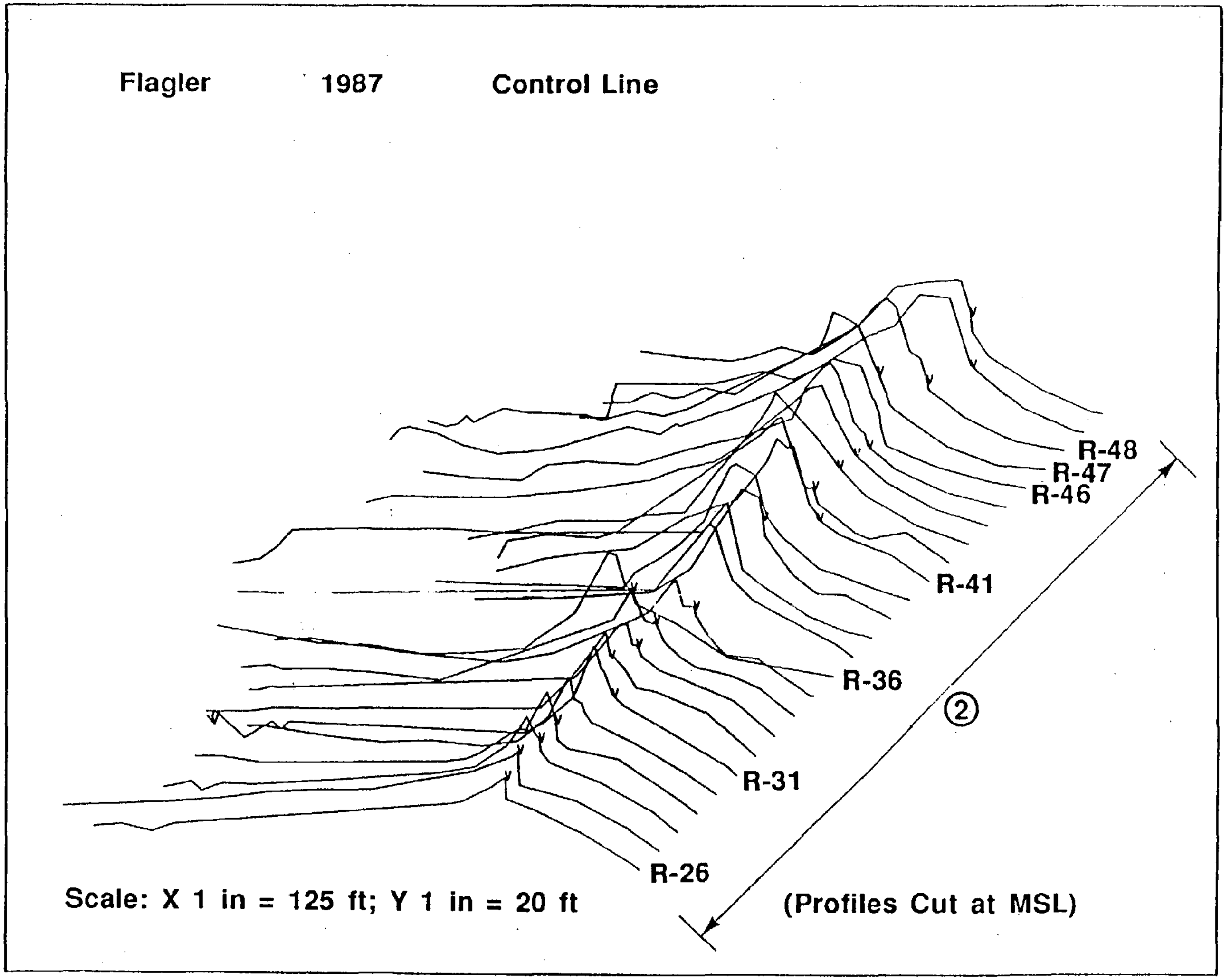
	l_b	h_b	l_{bb}	h_{bb}	l_{sc}	h_{sc}	l_{wf}	l_{lf}	l_1	l_2	h_1	h_2	h_3	l_{s1}	h_{s1}	h_{max}	h_{low}
R-4	75	5.5	95	11.5	25	5.5	85	90	0	0	28	0	0	0	0	0	24.5
R-5	90	7	60	9	50	11.5	50	250	0	0	29.5	0	0	0	0	0	26.5
R-14	50	2.5	35	4.5	110	3	60	50	0	0	19	0	0	0	0	0	13
R-19	25	3.5	120	7	64	8.5	13	90	0	0	25.5	0	0	0	0	0	6.5
R-23	25	1.5	45	5	92	5	85	70	0	0	28	0	0	0	0	0	6
R-27	40	4	20	7	60	2.5	95	65	0	0	31	0	0	0	0	0	5.5
R-31	25	2	40	6	26	1.5	70	100	0	0	27	0	0	0	0	0	7

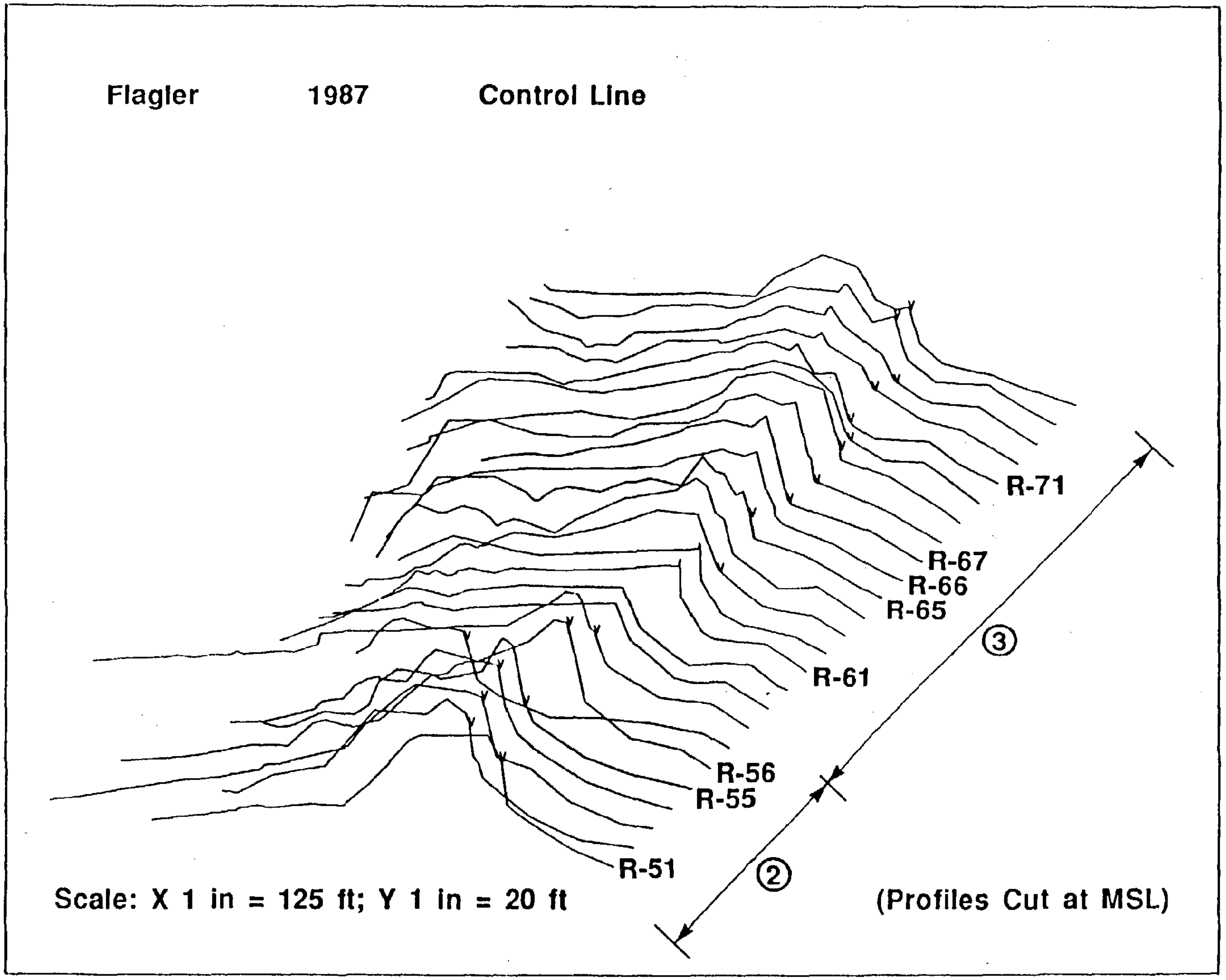
WALTON (CLASS=3)

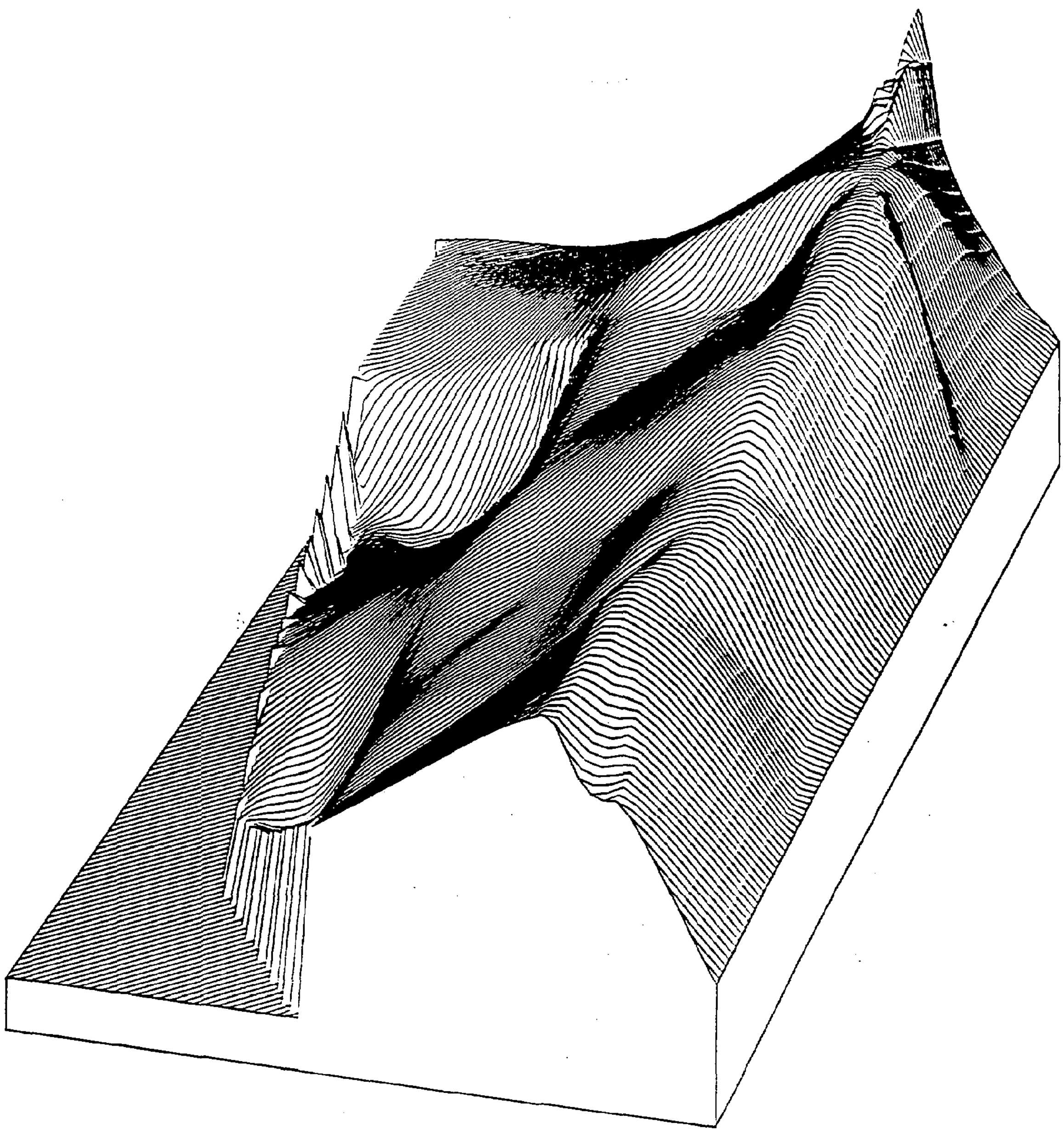
	l_b	h_b	l_{bb}	h_{bb}	l_{sc}	h_{sc}	l_{wf}	l_{lf}	l_1	l_2	h_1	h_2	h_3	l_{s1}	h_{s1}	h_{max}	h_{low}
R-85	50	3.5	0	0	100	7.5	75	200	0	0	33.5	0	0	50	34	36.5	0
R-86	50	4	60	6.5	65	15.5	35	280	0	0	38	0	0	45	30	38	36
R-89	50	4	80	8.5	42	7	65	155	0	0	29.5	0	0	0	0	29.5	27
R-90	90	5	125	9.5	50	14.5	0	350	0	0	50	0	0	50	8	35	0
R-94	40	5	25	5	0	0	0	180	0	0	6.5	0	0	0	0	13	8
R-105	40	5	60	7	15	0.5	70	100	0	0	28	0	0	60	14	15	0
R-114	12	2.5	37	5	55	2.5	30	25	0	0	32.5	0	0	30	13	31	30



Nassau
Sept-Dec 81
Control Line
R-46
R-42
R-41
R-36
R-33
R-31
R-26
1
(Profiles Cut at MSL)
Scale: X 1 in = 125 ft; Y 1 in = 20 ft

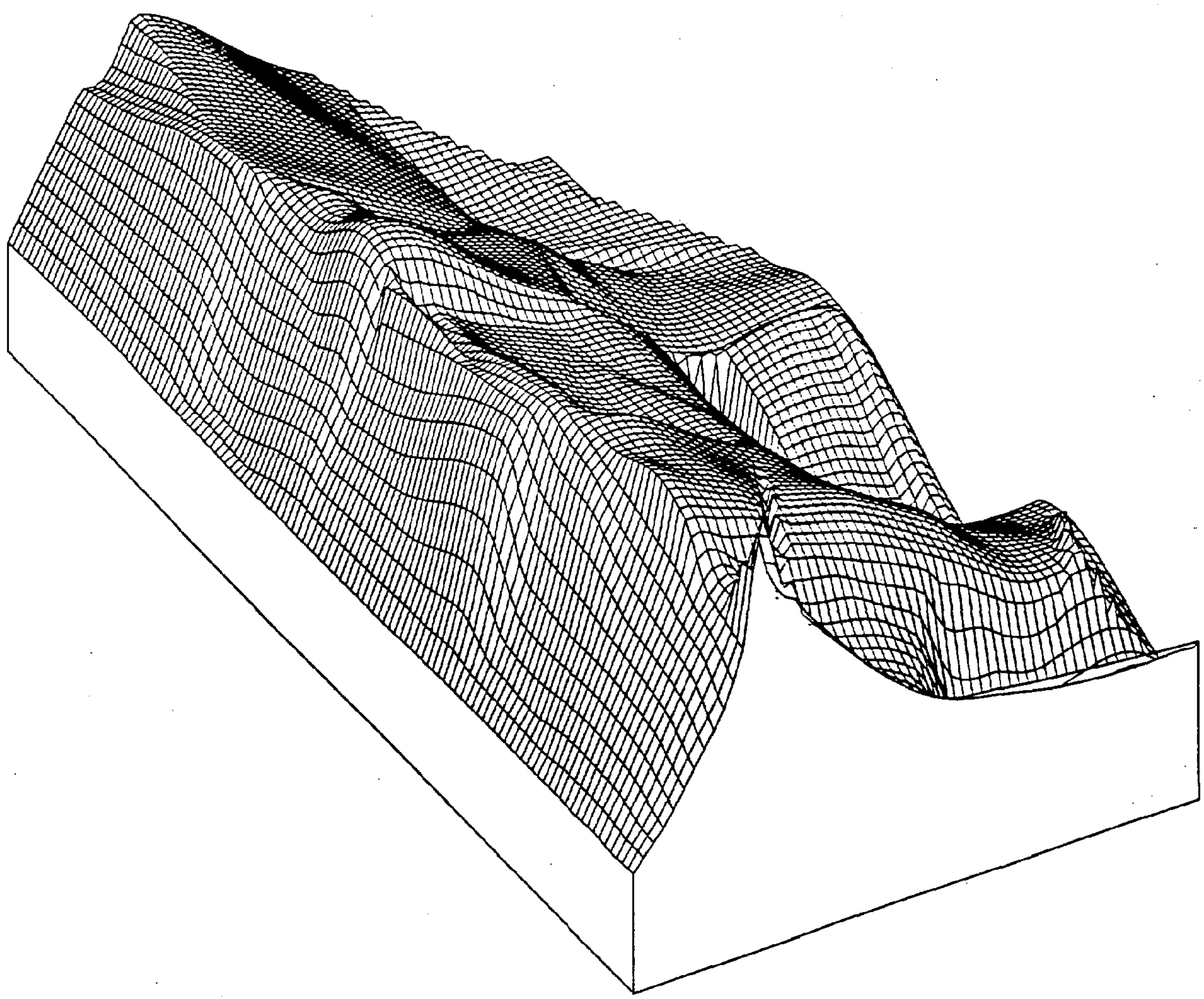

Flagler
1987
Control Line
R-48
R-47
R-46
R-41
R-36
②
R-31
R-26
Scale: X 1 in = 125 ft; Y 1 in = 20 ft
(Profiles Cut at MSL)


Flagler
1987
Control Line
R-71
R-67
R-66
R-65
R-61
R-56
R-55
R-51
3
2
Scale: X 1 in = 125 ft; Y 1 in = 20 ft
(Profiles Cut at MSL)



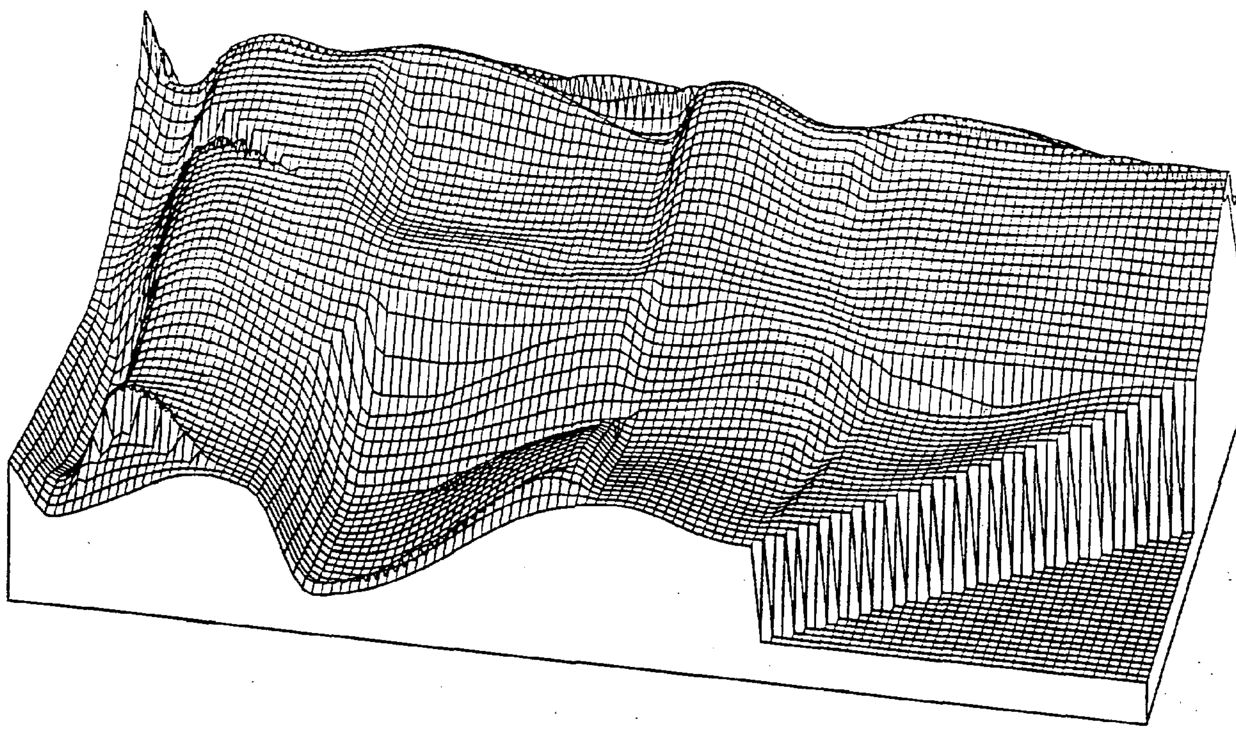
ST. LUCIE COUNTY BEACH TERRAIN

HUNTER/ESE



ST. LUCIE COUNTY BEACH TERRAIN

HUNTER/ESE



ST. LUCIE COUNTY BEACH TERRAIN

HUNTER/ESE