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Predicting Resistance and Stability of Vegetation in Floodplains

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PREDICTING RESISTANCE AND STABILITY OF VEGETATION IN FLOODPLAINS

by

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ABSTRACT

Predicting Resistance and Stability of Vegetation in

Floodplains

by

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To calculate flow or depth in a waterway, it is necessary to accurately determine the flow resistance. Past research has made considerable progress in predicting the roughness of nonvegetated uniform channels based on both theoretical and experimental investigations. However, to determine the flow resistance associated with vegetated compound flow channels and floodplains, the effects of the vegetation must be considered.

Recent advancements have led to greater understanding of the effects of partially submerged uniform vegetation in a waterway. However, to accurately determine flow resistance, it is imperative that the effects of both submerged and partially submerged vegetation be taken into account. It is also critical to account for the effects of multiple species and densities of vegetation throughout the waterway.

Extensive testing of both partially submerged and fully submerged vegetation was completed in the laboratory. Multiple species were tested together to represent various ecosystems commonly found in floodplains throughout the country. Results of the testing show that both geometric and biomechanical properties of the plants must be accounted for when determining vegetation resistance. Methods and procedures were developed to quantify these properties. Equations were also developed that provide a basis by which to quantify vegetation resistance.

The results of this study were compared to several sets of actual field data. The resistance values predicted by the equations were very close to those measured in the field. Use of the developed equations and procedures now provides those involved in the field of flood control a far more accurate tool by which to predict vegetation resistance than was previously available.

(155 pages)

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This dissertation, and all the experiences that led up to it, are dedicated to my grandfather, Nile, whose memory will always be with me.

Dave Werth

PREFACE

The funding agency for this project was the U.S. Army Engineers Waterways Experiment Station, Vicksburg, MS.; Project Name - Flood Control Channels; Work Unit Title - Stability of Vegetative Cover in Flood Control Channels; Work Unit No - 337A3; Federal Contract No - DACW39-94-K-0009. The study was the result of a proposal submitted in response to the U.S. Army Engineer Waterways Experiment Station Broad Agency Announcement, Open Channel Flow, HL-3. The project was coordinated with Dave Derrick and Gary Freeman of the U.S. Army Engineers Waterways Experiment Station. Portions of this dissertation were submitted to the funding agency in preliminary form, in 1996, as report No. USU-400 a&b entitled "The Study of the Resistance and Stability of Vegetation Ecosystem Plant Groupings in Flood Control Channels: Vol. 1 & Vol. 2," by William Rahmeyer and David Werth. The data contained in this dissertation are a part of the public domain and the writer cannot receive royalties for any part.

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LIST OF SYMBOLS

The following symbols were used in this dissertation:

a = Coefficient used by Kouwen and Li

A = Frontal area of an individual plant blocking flow

A* = Net area of a partially submerged plant blocking flow

A_S = Total cross sectional area of the stems of an individual plant

A_V = Unspecified vegetation area

b = Coefficient used by Kouwen and Li, dimensionless

b = Bed width

C = Chezy resistance coefficient

C_D = Drag coefficient of vegetation, dimensionless

dy/dx = Unit change in slope of water surface, dimensionless

D_S = Stem diameter

d_{84} = Bed material size that equals or exceeds 84% of particles sizes

E = Modulus of elasticity of the vegetation

f = Friction factor, dimensionless

F_B = Total force on channel bottom produced by vegetation

Fr = Froude number

F_{45} = The horizontal force necessary to bend a plant stem 45 degrees

g = Gravitational constant

H = Undeflected plant height

H' = Undeflected height of the leaf mass of a plant

H* = Effective submerged height of the leaf mass

I = Second moment of inertia of cross section of plant stem

k = Deflected roughness height

k_n = Unit conversion for Manning's Equation

L = Length of channel reach

M = Relative plant density

M' = Plant density ratio

m = Correction factor for channel meandering

n = Manning's resistance coefficient

n_b = Manning's resistance coefficient for bed roughness and vegetation

n_{base} = Manning's resistance coefficient for bed roughness

n_0 = Manning's resistance coefficient for base roughness

n_{veg} = Manning's resistance coefficient for vegetation

P = Wetted perimeter of channel

Q = Flow rate or discharge

R_h = Hydraulic radius (R=A/P)

R = Gross hydraulic radius

R_b = Hydraulic radius due to resistance of bed and vegetation

R_w = Hydraulic radius due to resistance of flume walls

$\mathbf{R}_E$ = Reynold's number

S = Bed or energy slope

S_f = Energy grade line slope

S_o = Bed slope

TL_A = Total leaf area

V = Mean channel velocity

V_{crit} = Critical velocity used by Kouwen and Li

V_P = Plant approach velocity at center of plant

V* = Shear velocity

V*/V = Resistance coefficient

Y_O = Flow depth

y_n = Normal flow depth

W = Plant width

γ = Specific weight of water

ν = Fluid dynamic viscosity

ρ = Fluid density

τ_o = Shear stress on channel bottom

CHAPTER 1

INTRODUCTION

Section I. Introduction

1-1. General. An important consideration for determining the stage-discharge relationship of a flood control channel is the effect or influence of vegetation on the overall head loss of the channel and the overbank flow. Plants or shrubs in the floodplain generally increase, but in some cases can decrease the total flow resistance during overbank flooding. The vegetation may be in place due to aesthetic reasons, natural conditions, or as planned measures for erosion control. The following is a study of the flow resistance testing of uniform plants, submerged and partially submerged, as well as nonuniform plants in ecosystem groupings. A plant ecosystem grouping is defined as a combination of two to three different sizes or types of plants typically found in a specific geographical region.

a. Resistance. To calculate the stage discharge relationship of a stream or river, it is necessary to accurately determine the flow resistance of the channel bed and sides. Past research has made considerable progress in predicting the roughness of uniform channels based on both theoretical and experimental investigations. However, to determine the flow resistance associated with floodplains and overbank flooding, the effects of emergent vegetation on the floodplains must be considered.

b. Vegetation Characteristics. A common problem associated with estimating the flow capacity of vegetated channels is the determination of the vegetation's hydraulic roughness parameters or coefficients. The most common of these roughness coefficients is Manning's *n*. The determination of these roughness coefficients is often carried out in the laboratory with the aid of flume testing. Empirical relationships developed from laboratory experiments apply only when natural flow conditions are similar to conditions that existed in the lab [29]. Due to the frequent changes in flow conditions that exist in natural channels, an analytical model that can be used for a wide range of flows and plant characteristics would be useful. This, coupled with the fact that there is very little published information for Manning's *n* on individual species of woody vegetation, demonstrates a need for such an analytical model.

c. Analytical Models. There has been considerable effort to develop an analytical model to estimate flow resistance in vegetated channels. The following is a brief introduction to current methods; a detailed description will follow in the literature review. To date, it appears that the efforts have been focused primarily on grasses or rigid objects. There is a trend toward designing vegetated channel linings not only for maximum flow conveyance, but also to improve aesthetics and habitat, minimize environmental impact, and provide erosion protection [10]. This has led to an increased use of woody vegetation in as channel lining. Recently work has been done by Fischenich [11] to quantify the resistance due to partially submerged woody vegetation. However, the equations proposed by Fischenich are applicable only to partially submerged vegetation. While Fischenich clearly states the importance of defining plant blockage area, the proposed methodology does not lend itself well to field applications. In addition, Fischenich's method acknowledges the fact that flexibility is important, but a relative measure or modulus of stiffness E is not included in his work. The results of the following study and recent work by Fathi-Maghadam and Kouwen [9] show that E is an important parameter that should not be ignored. The methodology suggested by Fathi-Maghadam and Kouwen reinforces the necessity of including plant stiffness, but suggests a time-intensive procedure for determining E. In addition, the analysis of Fathi-Maghadam and Kouwen was also limited to partially submerged vegetation. A practical, field-applicable procedure for determining blockage area and plant stiffness is presented in this study. A methodology will also be developed to handle completely submerged conditions and vegetation with varying density of plants per unit area.

d. Biomechanical Properties. Kouwen and Li [18] proposed a method for determining flow capacity that utilizes the biomechanical properties of vegetation. This method was developed for various grasses and is based primarily on the flexibility of the vegetation. Kouwen and Li's method was modeled using flexible plastic strips, those of which the mechanical properties are known or easily determined. Woody vegetation does not possess the same biomechanical properties as grasses; therefore, Kouwen and Li's model likely does not apply, as is, to this situation.

e. Guidelines. The U.S. Army Corps of Engineers (USACOE) is currently developing guidelines and an engineering manual for the design of vegetated channels that utilize various species of woody vegetation [12]. The determination of flow roughness factors, primarily Manning's n, is being conducted through laboratory testing on specific species. These tests are being conducted at the Utah Water Research Laboratory [25], [26]. While it is possible to determine Manning's n for individual species and varying flows, it is a time-consuming and costly procedure. Based on the results of this study, the following five (5) methods of determining resistance have been proposed.

(1) The first is a large flume test bed in which backwater curves under steady flow conditions are measured for large number of plants. While this method is the most accurate, it is both time consuming and expensive.

(2) A second method, one in which the USACOE has expressed interest, is to test or model individual plants, in a small sectional flume, and attempt to achieve results similar to large flume testing [25]. The flexibility and cost advantages of small-scale testing would be considerable.

(3) A third method, even more cost effective, yet somewhat less reliable would be a model which could accurately predict flow resistance with an in situ field method of determining the biomechanical properties of individual plant species.

(4) A fourth method, similar to (3), would be a model based on general tables of plant characteristics with less extensive field measurements.

(5) The fifth, and least reliable alternative would be to use currently available general tables of roughness values for vegetation.

Section II. Objectives

1-2. General. Having stated the necessity of developing improved methods by which to quantify vegetation resistance, the three primary objectives and the resulting subobjectives are presented in the following list:

a. Objective 1. Develop a set of equations to quantify vegetation resistance for nonrigid flexible vegetation.

(A) Determine the effects of plants with multiple stems;

(B) Determine the effects of groupings of different sizes and types of plants;

(C) Determine the effects of dormant plants without leaves;

(D) Determine the effects of plant configurations on sediment transport;

(E) Investigate the importance of plant density on floodplain resistance.

b. Objective 2. Develop methodology and procedures for determining vegetation resistance for both submerged and partially submerged flow conditions.

c. Objective 3. Correlate the drag force of individual plants as tested in the sectional flume with drag forces determined in the large flume. In addition, develop a model, based on the biomechanical properties of woody vegetation, which accurately determines the drag force associated with individual species.

d. Objective 4. Develop methodology to quantify the plant stiffness and blockage area for flexible woody vegetation.

Section III. Experimental Tasks

1-3. General. The experimental tasks of this study included data collection both before and during flume testing. Biomechanical and geometric properties of the plants were recorded before testing. Backwater curves for varying flow conditions and plant groupings were measured in the large flume. Strain on individual plants was measured in both the large and sectional flume. Velocity profiles in both the large and sectional flume were recorded. Scour and erosion effects were also quantified during varying velocity profiles and plant groupings. The following report includes: chapters on background material; test setup; test plants; test procedures; test results of resistance and drag forces; data analysis and methodology to predict resistance; an example of calculating roughness for a set of field conditions; a comparison of calculated or predicted values with measured data from several field studies; and a summary of conclusions and recommendations. Observations of plant and sediment movement were recorded on 35mm color slides and on 8mm videotape.

Section IV. Summary

1-4. General. This study will suggest methodology to quantify resistance by vegetation in floodplains. Methods for uniform plants as well as multiple nonuniform plant ecosystems are developed. This methodology includes both submerged and partially submerged flow conditions. Methods for both data collection and field applications will be covered. It is expected that the research completed in this study will provide valuable assistance to those involved in the field of flood control.

CHAPTER 2

LITERATURE REVIEW

Section I. Introduction

2-1. General. A significant amount of data has been published on roughness coefficients for grasses and large woody vegetation such as that found on established wood lots. However, no published information on individual species of small woody vegetation was found. For the purpose of this study, small woody vegetation has been defined as deciduous or coniferous vegetation on the order of 1 to 6 feet tall. This includes both young immature trees and developed shrubs and dwarf species such as those used for ornamental landscaping that only reach a few feet in height at maturity.

a. Need. A specific need for testing on these types of vegetation, specifically those found in floodplains, has been defined by the U.S. Army Corps of Engineers (USACOE). The USACOE has been called upon to utilize this vegetation as a method to provide soil stabilization in floodplains and flood control structures. The diversity of species tested is needed not only to minimize flood impact, but to also provide aesthetic value. In addition, more emphasis is being placed on planting vegetation that also provides wildlife habitat and forage.

Section II. Resistance Equations

2-2. Manning's Equation. Manning's Equation (Equation 2-1) is the most commonly utilized equation for defining the resistance to flow in waterways.

$$V = \frac{k_n}{n} R_h^{2/3} S^{1/2} \tag{2-1}$$

where V is the mean velocity in feet per second, R_h is the hydraulic radius in feet, n is Manning's roughness coefficient, and $k_n = 1.486$ when using English units and 1.0 when using SI units. A range of values for n have been published that account for resistance due to vegetation. While this range provides a general guideline, engineers are being called upon more and more to design under increasingly stringent criteria. This has created a need to determine more accurate roughness coefficients for specific types of vegetation. It is no longer acceptable to assign a single constant n value to encompass all the vegetation in a specific reach of waterway, but to develop a compilation of n values including several species and sizes of plants.

2-3. Shear Velocity. As defined by Manning's equation, n is the coefficient encompassing the vegetation resistance characteristics. Another method of quantifying the resistance is the ratio of shear velocity to mean velocity, V*/V. This has been used in theoretical developments by Prandtl and Einstein and is very popular for predicting resistance due to bed forms in alluvial channels. Shear velocity is defined by Equation 2-2.

$$V^* = (g\ R_h\ S)^{1/2} \tag{2-2}$$

The shear velocity ratio (Equation 2-3) is a form of the ratio of shear stresses to inertial force.

$$\frac{V^{*}}{V} = \frac{\sqrt{g R_h S}}{V} = \left(\frac{\tau_o}{\rho V^2} \right)^{1/2} \tag{2-3}$$

Other resistance equations do use different roughness coefficients such as the Darcy-Weisbach friction factor f (Equation 2-6) or the Chezy C (Equation 2-7). However, the conversions from Manning's n are straightforward and the following equations can easily be converted to either C or f, [Eqn. 2-4 is for SI units only].

$$\frac{V^{*}}{V} = \sqrt{\frac{f}{8}} = \sqrt{g}\, C = n \sqrt{\frac{g}{R_h^{1/3}}} \tag{2-4}$$

$$n = \frac{R_h^{2/3} S^{1/2}}{V} \;\; (\mathit{in\ SI\ units}) \;\; = 1.486 \frac{R_h^{2/3} S^{1/2}}{V} \;\; (\mathit{in\ EI\ units}) \tag{2-5}$$

$$f = \frac{8 g R_h S}{V^2} \tag{2-6}$$

$$C = \frac{\sqrt{R_h S}}{V} \tag{2-7}$$

The V*/V resistance coefficient closely resembles the Chezy equation, except the shear velocity ratio is a true dimensionless coefficient.

2-4. Misunderstanding Manning's Equation. A critical misunderstanding concerning Manning's *n* is the assumption that *n* is an independent variable, and remains constant for changes in flow variables such as velocity and depth. Chow [6] recognized that *n* will vary with variables of geometry that include: surface roughness, vegetation, channel irregularity, channel alignment, silting and scouring, obstructions, and channel shape. The range of Manning's *n* published by Chow for vegetation was from 0.001 to 0.05 for moderately tall vegetation and from 0.05 to 0.10 for very tall and dense vegetation. Chow [6] was also one of the first to publish that Manning's *n* could vary with the flow variables of depth and discharge.

2-5. Additive Resistance. Cowan [7] formulated the first additive or linearization of *n* (Equation 2-8) that was basically the summarization of the effects of the primary flow geometries.

$$n = \left(n_o + n_1 + n_2 + n_3 + n_4\right) \cdot m_5 \qquad (2\text{-}8)$$

where n_0 is a base *n* value for straight, uniform, and smooth channels in natural materials; n_1 is an additive value to n_o which accounts for surface irregularities; n_2 is an additive value which accounts for variations in channel geometry in a cross section; n_3 is an additive value which accounts for obstructions; n_4 is an additive value which accounts for vegetation; and m_5 is a correction factor for the meandering or sinuosity of the channel. This study will use $n_b = n_0 + n_4$ to designate a roughness that includes the effect of vegetation as well as the base roughness.

a. Additive Values. Detailed tables of base and additive values can be found in publications by Chow [6], Benson and Dalrymple [5], Barnes [4], and others. The derivation of Cowan's additive equation (Equation 2-8) is based in part on the assumption that velocity, slope, and depth are constant across the flow channel. This assumption restricts the application of Equation 2-8 to uniform channels or uniform subsections, and prevents the use of the equation to determine an average channel resistance coefficient for situations such as overbank flooding.

Section III. Channel Resistance

2-6. Variation with Depth or Hydraulic Radius. Limerinos [21] recognized that Manning's base n_0 was not just a function of relative roughness, but varied with depth or hydraulic radius. From the analysis of 11 different streams he formulated Equation 2-9.

$$n_0 = \frac{.0926 \cdot R_h^{1/6}}{1.16 + 2 \cdot \log\left(\dfrac{R_h}{d_{84}}\right)} \tag{2-9}$$

where d_{84} is the bed material size that equals or exceeds 84% of the particle sizes. The limitations of Equation 2-9 include that the equation can only be applied to a narrow range of natural channels, and that the particle size data must be known. Limerinos's equation does not account for the effects of vegetation.

2-7. <u>Variation with Slope.</u> Jarrett [13], [14] and [15] recognized that Manning's n varied with hydraulic radius, and stated that Manning's n should vary with the slope of the energy grade line. Jarrett did his work analyzing high-mountain streams, and derived Equation 2-10.

$$n_0 = 0.39 \cdot S^{0.38} \cdot R^{-0.16} \qquad (2\text{-}10)$$

Jarrett's analysis had an average standard error of 28% for Equation 2-10, and the equation is limited to stream slopes from 0.002 to as high as 0.052. In three of the streams he analyzed, the flow was affected by bank vegetation, which created additional turbulence and resistance. However, he did not include this datum in the development of Equation 2-10, and therefore an additive method similar to the methods presented by Cowan [7] or Arcement and Schneider [2] would be needed along with Equation 2-8 to determine the overall roughness when vegetation is present.

Section IV. Vegetative Resistance

2-8. <u>Predicting Drag Force.</u> While it is theoretically possible to relate drag force to Manning's n, the difficulty lies in predicting the drag an individual species will exert on the channel bottom. Various methods have been proposed to predict drag based on the biomechanical properties of plants. Biomechanical properties are physical plant properties such as flexibility, stiffness, and modulus of elasticity that define the structural characteristics of the plant, but are based on biological attributes. These characteristics vary not only between different species but among the same species as well. There are numerous variables affecting these properties including climate, age, disease, and soil characteristics. These variations impose a need to determine the biomechanical properties on a site-by-site basis.

2-9. Grasses. The bulk of the published work on biomechanics has dealt primarily with grasses. Historically, grasses were the primary method of bank stabilization. This eliminated a need to study the biomechanical properties of small, woody vegetation. In present times however, the need to utilize woody vegetation has been established, thus requiring methods by which to define the plants biomechanical properties. While most published work covers only grasses, it provides both a background and a understanding of biomechanical properties as they pertain to fluid resistance. It will, therefore, be useful to discuss some of the methods others have used to determine resistance in grasses.

2-10. Modifying Manning's Equation for Grasses. Abdelsalam et al. [1] analyzed four wide, vegetated canals in Egypt. They modified Manning's equation to provide Equation 2-11, which then accounted for resistance in wide canals with submerged, grassy vegetation.

$$V = \frac{1.486}{n} \cdot Y_O^{1.62} \cdot S^{0.5} \tag{2-11}$$

where Y_O is the depth of flow. The limitations associated with this equation are that it only applies to vegetation growing within the main channel, and that the vegetation needs to be submerged. Also, the vegetation is confined to plant types similar to grasses and not to shrubs or woody types of vegetation.

2-11. Deflection Height. Recent studies on flow resistance with grasses include the research by Kouwen and Li [18]. They adapted (Equation 2-12) the work by Keulegan [17] to use the deflected height, *k*, of grass instead of the roughness height of the channel bottom. Their work provides a means of determining Manning's *n* by comparing grasses to flow tests of artificial plastic strips. They show that grasses behave similarly to artificial plastic strips, and that Manning's *n* (Equation 2-13) is basically a function of the relative roughness, k/Y_O, where *k* is the deflected roughness height and Y_O is the normal depth. The coefficient $n_0 = n_b$ and includes the effect of vegetation.

$$\frac{1}{\sqrt{f}} = a + b \log\left(\frac{R_h}{k}\right) \tag{2-12}$$

$$n_o = n_b = \frac{Y_O^{1/6}}{\sqrt{8g\left[a + b \cdot \log\left(\frac{Y_O}{k}\right)\right]}} \tag{2-13}$$

where *a* and *b* are regression constants dependent on shear velocity and the critical shear velocity. Because there are no experiments with natural vegetation that publish values for the parameter *k*, Kouwen and Li [18] have proposed a method utilizing Equation 2-14 as a means of determining k based on physical parameters of the vegetation.

$$k = 0.14 \cdot H \cdot \left(\frac{\left(\frac{M' E I}{\gamma y_n S} \right)^{0.25}}{H} \right)^{1.59} \qquad (2\text{-}14)$$

where E is the modulus of elasticity of the vegetative material in Pascals; I is the second moment of the cross-sectional area of the plant stems in meters to the fourth power; M' is the relative density defined as the ratio of the stem count to a reference number of stems per unit area; H is the undeflected vegetation height; and γ = the specific weight of water in Newtons per cubic meter. Their method first assumes a value for the product of $M'EI$ and a value for the flow depth of the channel. Then, through an iterative process, $M'EI$ is optimized. It should be noted that the relative density M' used by Kouwen and Li is not the same plant density used in this study, and that it is not truly dimensionless since the reference number of stems used in their report is based on one stem per square meter. The values of exponents recommended by Kouwen and Li for grasses are shown in Table 2-1.

TABLE 2-1. Exponents for Kouwen and Li's Equations

a	b	V^*/V_{crit}
.15	1.85	$V^*/V_{crit} < 1$
.2	2.7	$1 < V^*/V_{crit} < 1.5$
.28	3.08	$1.5 < V^*/V_{crit} < 2.5$
.29	3.5	$2.5 < V^*/V_{crit}$

where the value of V^*/V_{crit} is found from Equation 2-15.

$$\frac{V^*}{V_{crit}} = 0.028 + 6.33\,(M'EI)^2 \tag{2-15}$$

2-12. Limitations of Using Deflection Height. Since the method by Kouwen and Li applies to densely packed grasses, it cannot be directly applied to floodplains that contain other types of vegetation. It has to be assumed that the above method predicts a base value of roughness, $n_o = n_b$, since the densely spaced grass completely covers the soil or base material. Shrubs and woody vegetation would be much more difficult to model using artificial roughness because the M'EI would have to be experimentally determined for each plant species, plant size, and plant spacing. Equation 2-15 also does not account for the separate effects of velocity and flow depth on any distortion or change in shape of a plant.

2-13. Modeling with Plastic Strips. Kouwen and Unny [19] published results of another study relating the amount of bending of plastic strips to boundary shear. This relationship can be seen in Equation 2-16.

$$\frac{k}{H} = \frac{3.57}{H} \left(\frac{MEI}{\rho u_*^2}\right)^{1/4} - 0.286 \qquad (2\text{-}16)$$

where u_* = shear velocity V^* and the other variables are previously defined.

a. Plant Form Parameter. The initial analysis performed by Kouwen and Unny included a plant form parameter. The experimentation, however, was performed with uniform plant spacing using strips of plastic to simulate grasses. With uniform spacing, the plant-form parameter was dropped. Woody vegetation varies considerably more than grasses, and plant shape should be included in this type of analysis. Kouwen and Unny recognized the lack of field data and suggest obtaining EI by measuring k, H, M and u_*. A limitation is that the stiffness is assumed to be constant over the entire plant length.

2-14. Early Studies of Plant Deformation. Research by Thompson and Roberson [29] did include the study of vegetation that deformed or distorted with velocity. They recognized that plants such as shrubs contributed to flow resistance from the blockage by the plants, while the channel bottom added to the total resistance from the roughness of the unoccupied channel bed. They also recognized that resistance of plants depends upon the plant size, plant shape, flexibility of the plant, the concentration or spacing of the plants, and the extent of the submergence of the plant. However, their studies were limited to tests with artificial, plastic rods. They included no actual plant data in their analysis, and they also did not publish any definitive equations or methods to determine roughness.

2-15. Crop Testing. Ree and Crow [27] tested actual plants for flow roughness but their work was limited to planted rows of crop types of plants such as wheat, sorghum, and grasses. Their tests were conducted in fields with very small slopes. While they did publish their results as graphical relationships of resistance versus velocity times hydraulic radius (*n* vs. *VR*), their test results were essentially independent of energy slope. Their results did show that the flow roughness coefficients of plants would decrease with increased velocity due to the bending of the plants. However, they did not attempt to quantify the amount that the vegetation roughness coefficients would decrease based on the biomechanical properties of the vegetation.

Section V. Vegetative Resistance Due To Drag Forces

2-16. Summation of Drag Forces. One of the most recent works on blockage and drag forces due to plants was published by Kadlec [16]. His work focuses on determining energy slope for wetland types of plants, especially grassy types of plants, and on wetland flows that are laminar to transitional in Reynold's number. Since his study was limited to fairly low velocities, his analysis was based on flow blockage of rigid plant stems and a small range of shallow flow depths. He did acknowledge that the determination of Manning's roughness coefficient *n* would require flow data for different depths and would be quite difficult. Kadlec proposed that flow resistance could be based on the summation of drag forces from individual plants, which is the basis for the theoretical development in this study.

2-17. Overbank Flooding with Large Vegetation. Usually the larger vegetation such as shrubs and trees is found in the floodplains adjacent to the main channel. This type of vegetation is a major influence on flow depth and resistance during situations such as overbank flooding. Since the larger types of vegetation constitute much of the resistance within floodplains, Petryk and Bosmajian [24] proposed a method to calculate flow resistance based on the drag forces created by the larger plants. They derived Equation 2-17 for Manning's n by summing the forces in the longitudinal direction. The forces include pressure forces, the gravitational force, shear forces, and the drag forces.

$$n = n_b \cdot \sqrt{1 + \left(\frac{C_D \ \Sigma A_i}{2g A L} \right) \cdot \left(\frac{1.486}{n_b} \right)^2 \cdot \left(\frac{A}{P} \right)^{4/3}} \tag{2-17}$$

where n is the total roughness coefficient, n_b is the total boundary roughness, C_D is the effective drag coefficient for the vegetation the direction of the flow, A is the cross-sectional area of the flow (in square feet), ΣA_i is the total frontal area of vegetation blocking the flow in the reach (in square feet), L is the length of the channel reach being considered (in feet), and g is the gravitational constant (in feet per square second).

a. Blockage Area. The expression $C_D\Sigma A/(AL)$ represents the vegetation blockage, or the density of vegetation in the flood plain. This expression must be either directly or indirectly measured as a total blockage of flow. The total additive base n_b is determined by Cowan's additive method (Equation 2-8), except that the additive roughness n_4 for other types of vegetation is excluded.

b. Limitations. There are several limitations to using Petryk and Bosmajian's Equation 2-17. The channel velocity must be small enough to prevent bending or distortion of the shape of the vegetation, and large variations in velocity cannot occur across the channel. Vegetation such as grasses and shrubs is then excluded. Vegetation must also be distributed relatively uniformly in the lateral direction. Finally, the flow depth must be less than or equal to the maximum vegetation height. During flooding, the velocities over the floodplains can be relatively high, and large degrees of bending and distortion of vegetation will occur. Vegetation can also vary widely across a floodplain, and depths often submerge vegetation. However, when tree trunks dominate sections of a floodplain, this method can be used for predicting the total roughness coefficient.

Section VI. Combined Channel and Vegetative Resistance

2-18. Further Modification of Petryk's Method. Arcement and Schneider [2] further developed Petryk's method by stating that the portion of the vegetation that cannot be measured directly or calculated as rigid flow blockage should be included in Cowan's formula as n_V (Equation 2-18).

$$n_b = n_o + n_1 + n_2 + n_3 + n_V \tag{2-18}$$

where n_V accounts for vegetation, such as shrubs and grass, on the floodplain that cannot be measured directly or calculated as a flow blockage. Equation 2-17, as defined by Petryk, accounts only for rigid and measurable vegetation such as tree trunks.

a. Including Vegetation. By utilizing n_V, it should then be possible to use Equations 2-17 and 2-18 to include the effects of trees, grasses, and shrubs in calculating the total resistance of a vegetated channel. The total base roughness n_b of Equation 2-18 can be determined from either a base n_o or a grass base roughness (Equation 2-14). The total roughness n is calculated from correcting the total base roughness n_b for the effects of trees by Equation 2-17. The additive roughness coefficient n_V in Equation 2-18 is due to the effects of vegetation such as shrubs and woody vegetation. The main purpose of this study is to develop a database and methodology to determine n_V and n_b.

Section VII. Flow In Compound Channels

2-19. Introduction. When dealing with overbank flooding, not only does flow occur in the main channel, but often in two entirely different floodplains. The combination of main channel, left bank, and right bank make up a compound channel. In this case, the application of equations developed for flow in uniform channels is no longer valid. Vegetation is almost certainly going to vary between the main channel and the banks or floodplains. Any methodology developed to deal with flow in compound channels must be able to account for changes in vegetation or roughness characteristics. Cowan's additive equation (Equation 2-8) and the equations to predict resistance from vegetation (Equations 2-19, 2-20, and 2-21) are all based on the assumption of constant velocity, energy slope, and flow depth across the channel. Many flood channels such as those with overbank flooding do not have uniform cross sections with uniform flow resistance. Special considerations must be taken to calculate the flow depths and flow resistance of these compound channels, especially when vegetation is present.

2-20. Channel Variations. Chow [6] and Cowan [7] have shown that there are many factors that affect the boundary roughness and flow resistance. Even within the main flow section of a compound flood channel, these factors can vary. However, the roughness and flow resistance will significantly vary from subsection to subsection for compound channels with floodplains and overbank flooding. Main flow channels that have different roughness along sections of the wetted perimeter can be referred to as composite channels. Determining the total discharge for a compound channel that includes a composite main channel can be complicated. Currently, there are two different methods used: a flow conveyance method, and an equivalent flow resistance method.

2-21. Flow Conveyance Method. The flow conveyance method is a mathematically rigorous method for compound channels, and has been assumed by most researchers to be the most fundamentally correct and accurate. Masterman and Thorne [23] apply the law of continuity when they state that the total discharge is equal to the sum of the discharges of the main channel and its floodplains. This is possible when the assumption is made that the flow in all parts or sections of the channel is caused by the same energy grade line, that is, the energy grade line is the same everywhere in the compound channel. With the assumption of constant energy slope, the discharge of each section can be solved for interactively, section by section, and by checking to ensure that the water-surface elevation is the same for each section. The total discharge of the compound flood channel is then the sum of the discharges of each channel section.

2-22. Equivalent Resistance Method. The equivalent resistance method applies Manning's formula to the entire compound flood channel. It is necessary to compute a compound roughness, or an equivalent resistance, for the entire channel.

a. Development of Chow's Equations. Chow [6] presented three equations for determining an equivalent resistance. The development of these equations is based on applying a weighting factor to each section of the compound channel and then combining them appropriately. All three equations are based on a constant water surface elevation. To determine the equivalent roughness, the total area is subdivided into N parts, of which the wetted perimeters $P_1, P_2, ..., P_N$ and the roughness coefficients $n_1, n_2, ..., n_N$ for each section are known.

b. Chow's First Equation. The most widely used equivalent resistance equation is based on the assumption that each section of the total area of the channel has the same mean velocity. The equation was intended for use with composite channels with variable roughness and not for use with compound channels. However, the equation is sometimes used for compound channels even though large errors can occur. Using this assumption, the equivalent roughness may be determined by the following equation:

$$n = \left(\frac{\Sigma \left(P_N \cdot n_N^{1.5} \right)}{\Sigma P_N} \right)^{2/3} \qquad (2\text{-}19)$$

Dracos and Hardegger [8] have suggested using this equation for compound flood channel with subsections of fairly low flow resistance and smooth boundaries. Sections with vegetation typically have rough boundaries and high resistance, and would not be suitable for use with this equation.

c. Chow's Second Equation. The second equivalent resistance equation presented by Chow for determining an equivalent roughness is based on the assumption that the total force resisting the flow, KV^2PL, is equal to the sum of the forces resisting the flow in each section of the cross section. This equation also uses the assumption that each part of the total area has the same mean velocity.

$$n = \left(\frac{\Sigma \left(P_N \cdot n_N^{2} \right)}{\Sigma P_N} \right)^{1/2} \qquad (2\text{-}20)$$

d. Chow's Third Equation. The third equation given by Chow for determining an equivalent roughness is based on the assumption that the total discharge of the flow is equal to sum of the discharges for each area within the total area [22].

$$n = \frac{\left(\Sigma P_N \cdot \Sigma R_N^{5/3}\right)}{\Sigma\left(\frac{P_N \cdot R_N^{5/3}}{n_N}\right)} \tag{2-21}$$

where $R_1, R_2, \ldots, R_N$ are the hydraulic radii of each section. Equation 2-21 is actually a flow conveyance equation since the velocity does not have to be constant throughout the cross section.

Section VIII. Vegetation in Compound Flood Channels

2-23. Introduction. The flow conveyance method and Equation 2-21 will yield the same results for a compound flood channel. The equivalent resistance method and Equations 2-19 and 2-20 will yield questionable results for compound channels with vegetation if the assumption of equal velocity is made. It is inherent that the resistance of channel sections with vegetation will be larger than the resistance for the main channel, and will then experience lower velocities than the main channel. The assumption of constant velocity is invalid and the use of the equivalent resistance method is questionable for vegetated floodplains. The difference in results between the two methods will, in part, depend on the magnitude of the resistance of the vegetation.

2-24. Limitations of Equations. Both the flow conveyance method and Equation 2-21 utilize an iterative solution to solve for the flow depth or total discharge. The advantage of using Equation 2-19 or 2-20 to obtain the equivalent resistance is that they provide a direct solution for depth or discharge. However, if the flow resistance should vary with velocity and/or depth, the solution by either method will become more complicated. The equations and methods of the previous section on flow resistance were limited to flow sections of uniform resistance and velocity. However, these equations can be applied to each individual subsection of the compound flood channel and used with either the flow conveyance or equivalent flow resistance methods.

2-25. Additional Works. A recent publication by Masterman and Thorne [23] presents the application of Kouwen and Li's [18] method for grasses with calculations in a compound channel. In their paper, they note that a rational method for emergent, non-flexible vegetation is being developed. Additional information on flow resistance and compound flood channels can be found in a very comprehensive literature review by Craig Fischenich [10].

Section IX. Sediment Transport With Vegetation

2-26. Introduction. It is common knowledge that the presence of vegetation in a channel or floodplain will affect the sediment transport and the scour or erosion of the channel bottom and sides. Vegetation will certainly reinforce and strengthen the soil surfaces through the development of root systems. The effective soil boundary is then more resistant to soil movement and erosion. Vegetation can also impede the movement of the contact portion of the bed load [3], and prevent or stabilize bed forms.

2-27. Vegetation Effects. Another common belief is that the presence of vegetation increases flow resistance, which results in the reduction of flow velocity and increased depth. The reduced velocity will then reduce the sediment transport of the channel and reduce the forces necessary to cause scour and erosion. Li and Shen [20] have developed the theory to explain how the retarding flow rate is the result of the drag forces on tall vegetation, and developed the methodology to predict the reduction of sediment load.

2-28. Limitations of Li and Shen's Study. A limitation of Li and Shen's study is the exclusion of the effects of the leaves and branches of vegetation. Also, their investigations only studied cylinders, and relied on the assumption of uniformly distributed bed shear. The development of their theory was based on a horizontal, two-dimensional flow field around multiple cylinders. Tests of actual vegetation were not available for their study, and the two-dimensional analysis precluded the consideration of vertical velocity components. The blockage produced by plant leaves and branches could produce vertical velocity components that would then create flow vortices and local scour. Local scour immediately upstream of bridge piers is a classical example of this type of phenomenon [28]. Another effect of the plant foliage would be the formation of a layer or blanket that would divert flow beneath the foliage. Flow diverted beneath the foliage blanket could result in increased velocities along the channel bottom.

2-29. Fathi-Maghadam and Kouwen. In addition to the writer, the most recent work found on nonrigid vegetative roughness was by Fathi-Maghadam and Kouwen [9]. In a 1997 ASCE article titled "Nonrigid, Nonsubmerged, Vegetative Roughness on Floodplains," Fathi-Maghadam and Kouwen present a method of quantifying vegetation resistance. While the work dealt only with partially submerged vegetation, many important concepts were presented or reinforced. While Fathi-Maghadam and Kouwen were unaware of previously published work by Rahmeyer and Werth [25] and Rahmeyer et al. [26], they independently concluded that Manning's *n* varied greatly with channel-flow velocity due to bending and flow depth as a result of increased flow blockage area. Fathi-Maghadam and Kouwen also reinforced the concept of shear velocity V* as a fundamental basis in the theoretical development of resistance equations. They also stated that the modulus of elasticity E is an important biomechanical plant parameter that should not be ignored. The dimensional analysis performed by Fathi-Maghadam and Kouwen yielded the following functional relationship shown as Equation 2-22.

$$C_D \left(\frac{A}{\forall}\right) h = f_4 \left(\frac{\rho V^2 Y_O^4}{J}\right) \qquad (2\text{-}22)$$

where C_D= the drag coefficient, $\forall = ay_n$, $a=l_1l_2$, l_1 and l_2 are cross-wise and flow-wise lengths of blockage area, $J = EI$, E is the modulus of elasticity, and I is cross-sectional moment of inertia of the plant.

2-30. Vegetation Stiffness and Blockage Area. Fathi-Maghadam and Kouwen [9] proposed that the flexural rigidity ($J = EI$) is the parameter that accounts for the effect of stiffness and ability to resist bending. They also proposed that E be determined by resonance frequency. They have proposed a method based on the theory that a beam with a given mass and elasticity may experience one or more resonance frequencies of vibration depending on damping. Fathi-Maghadam and Kouwen propose measuring each species using a device that vibrates the plant and measures the resonance frequency. While this method is theoretically and fundamentally correct, it is most likely an impractical method for field applications. The writer intends to propose what may be a more practical method by which to quantify flexural stiffness. Fathi-Maghadam and Kouwen have also indicated that blockage area is an important parameter that should not be ignored. They present this as the momentum absorbing area (MAA) and suggest that it be addressed with a volumetric approach rather than a frontal area.

2-31. Tests Conducted. Fathi-Maghadam and Kouwen utilized a small flume and used pine and cedar models to obtain their data. They used an approach similar to Rahmeyer and Werth [25] and Rahmeyer et al. [26], in that the drag force was measured using strain gauges. Their results agree with the writers' previous work in that resistance decreases with increasing velocities while the plants streamline with the flow. They reported that with partially submerged vegetation, the plant density is the dominant factor. It was also reported that their data need to be validated for larger depths. Fathi-Maghadam and Kouwen were also limited to partially submerged vegetation. The writers' data include both submerged and partially submerged vegetation data and a considerably broader range of vegetation. This coupled with the difficulty of applying the equations proposed by Fathi-Maghadam and Kouwen to actual field applications clearly indicates the need to further investigate and develop resistance methodology as applied to both submerged and partially submerged vegetation. Practical field applications also dictate the need to further develop the methodology to include multiple plant groupings and a method where the required information can be easily obtained and applied in the field.

2-32. Fischenich. A recent publication by Fischenich entitled "Velocity and Resistance in Densely Vegetated Floodways" [11] is probably the most recent work that addresses the issue of developing vegetation resistance equations for use in vegetated floodplains. Fischenich acknowledges that methodology must be developed for compound channels when dealing with varying roughness. He also acknowledges that variations in vegetation should be accounted for. Fischenich discusses the different flow regimes that occur when plants are submerged and partially submerged and suggests the use of separate methodologies to deal with each condition. Fischenich further refines the approach of summing drag forces, which was developed by Kadlec [16] and is discussed in section 2-16. However, the methodology presented by Fischenich is limited to partially submerged grasses and three uniform plants. A major limitation to the approach suggested by Fischenich is a working method by which to quantify the flexibility of vegetation. Fischenich does not suggest the use of a parameter such as the modulus of elasticity or a plant stiffness parameter. He does suggest using parameters such as vegetation height and blockage area, which can be somewhat related utilizing a lumped parameter accounting for the drag coefficient. Fischenich suggests utilizing laboratory techniques such as those developed by Rahmeyer and Werth [25] to determine the drag coefficient, but does not suggest a field technique for determining flexibility. Fischenich developed the following Equation 2-23 to describe resistance. This equation was developed with data from the earlier phase 1 testing of this study [25].

$$n = \frac{k_n R^{0.167} y}{2.5\sqrt{g}\left[\int_a^b \ln\left(\frac{z-h+\frac{h}{11.5C_d A_v}}{0.13e^{-(C_d A_v-0.4)^2}h}\right)dz+\int_0^h 1.26h^2\left(\frac{\cosh(11C_d A_v z)}{\cosh(11C_d A_v h)}\right)^{0.5}dz\right]} \tag{2-23}$$

where A_v is the unspecified vegetation area, z is a roughness height, and y is the flow depth.

CHAPTER 3

DEVELOPMENT OF ANALYSIS EQUATIONS

Section I. Development of Resistance Methodology

3-1. Drag Force. When an object is exposed to fluid flow, the fluid exerts a force on that object. This force is defined as drag force. The drag experienced by an object exposed to fluid flow is defined by Equation 3-1.

$$F_D = \frac{C_D \, A \, \rho \, V^2}{2} \tag{3-1}$$

where F_D is the drag force in pounds, C_D is the drag coefficient, A is the surface area normal to the velocity, ρ is density of the fluid medium, and V is the mean velocity of the fluid. If the surface area of a plant or shrub is known, as well as the C_D value, it is theoretically possible to determine the drag exerted by the plant on the channel bottom for a given flow situation.

3-2. Bottom Force. The shear stress caused by vegetation is proportional to the total bottom force F_b, which is produced by the vegetation on the channel bottom. The total bottom force is equivalent to the sum of the drag forces exerted by each plant. Therefore, the total bottom force can be defined by Equation 3-2.

$$F_b = \tau_o \cdot Area_{bottom} = \sum F_D \tag{3-2}$$

3-3. Kadlec's Hypothesis. Kadlec [16] presented a hypothesis that the flow resistance from vegetation can be thought of as the result of the sum of the total drag forces, F_D, and the shear stress produced by vegetation on the channel bottom. This hypothesis was the major premise for the analysis and formulation of the methodology for this study. The net bottom force is then equal to the sum of the drag forces from each plant and can be equated to the net bottom shear force produced by the plants. The net vegetation shear stress ($\tau_o = \gamma R_h S$) is also equivalent to total drag forces divided by the area of channel bottom, and is equivalent to the individual average drag force times the plant density (Equation 3-3).

$$\tau_O = \sum \frac{F_D}{area} = F_D M \tag{3-3}$$

where τ_o is the plant shear stress on the channel bottom, M is the plant density in number of plants per unit area, and F_D is the drag force produced by an individual plant.

3-4. Shear Velocity. The shear velocity V* is related to shear stress by Equation 3-4, and a commonly used roughness coefficient that is associated with shear stress is V*/V (Equation 3-5), where V is the mean flow velocity. The ratio of shear velocity to mean velocity, V*/V, is the classical form of roughness coefficient used by Prandtl and Einstein for theoretical development of the resistance due to roughness in natural channels.

$$V^{*} = \left(g R_h S\right)^{1/2} \tag{3-4}$$

$$\frac{V^{*}}{V} = \frac{\sqrt{g R_h S}}{V} = \left(\frac{\tau_o}{\rho V^2}\right)^{1/2} \tag{3-5}$$

The shear velocity and shear stress can then be related to drag force by Equation 3-6.

$$V^{*} = \sqrt{\frac{\tau_O}{\rho}} = \sqrt{\frac{F_D M}{\rho}} \tag{3-6}$$

where the drag force F_D is defined by Equation 3-1. *Vp* is the approach velocity to the plant, which should not be confused with the mean channel velocity *V*. By using the approach velocity *Vp,* Equation 3-1 can be modified to describe the drag force experienced by an individual plant. This is shown as Equation 3-7. The drag coefficient C_D can then be related to the resistance by Equation 3-8.

$$F_D = \frac{\rho\ C_D\ A\ V_p^2}{2} \tag{3-7}$$

$$C_D = \frac{2\ (V*/V)^2}{A \cdot M} \tag{3-8}$$

3-5. Coefficient Conversions. Other resistance equations use different roughness coefficients such as the Darcy friction factor *f* or the Chezy *C*. However, the conversions from Manning's *n* are straightforward and the following equations can easily be converted to either *C* or *f*.

$$\frac{V^*}{V} = \sqrt{\frac{f}{8}} = \sqrt{g}\,C = n\sqrt{\frac{g}{R_h^{1/3}}} \qquad (3\text{-}9)$$

$$n = \frac{R_h^{2/3}\,S^{1/2}}{V}\ \ (\textit{in SI units}) \ = 1.486\,\frac{R_h^{2/3}\,S^{1/2}}{V}\ \ (\textit{in EI units}) \qquad (3\text{-}10)$$

$$f = \frac{8\,g\,R_h\,S}{V^2} \qquad (3\text{-}11)$$

$$C = \frac{\sqrt{R_h\,S}}{V} \qquad (3\text{-}12)$$

By substitution, the roughness coefficients can then be related to the drag coefficient with the following equations, where K_n is the unit conversion for the Manning's equation (i.e., K_n = 1.4861 for E.I. units and K_n = 1 for SI units). The units of Kn are $L^{1/3}/t$.

$$C_D = \frac{2g\, n^2}{A \cdot M \cdot K_n^{\,2} \cdot R_h^{\,1/3}} \tag{3-13}$$

$$\frac{V*}{V} = \left(\frac{A \cdot M \cdot C_D}{2} \right)^{1/2} \tag{3-14}$$

$$n = K_n \cdot R_h^{\,1/6} \cdot \left(\frac{A \cdot M \cdot C_D}{2g} \right)^{1/2} \tag{3-15}$$

3-6. Blockage Area. The blockage area of an individual plant, A, is approximated by the effective height (H^*) times the effective width (W) of a plant. The blockage area is the frontal area of the plant as seen by the flow. The effective height can be defined as height of the leaf mass or area exposed to the flow. The effective width is defined in the same manner as being the width of the leaf mass exposed to the flow.

Section II. Development of Analysis

3-7. Drag Coefficients for Rigid Bodies. It has been well established that the drag coefficient for a rigid body is not a constant and varies with Reynold's number. Many past researchers [21] have established that the drag coefficient of a rigid body on a channel bottom will vary with flow depth or the depth of flow over the object. A wide range of studies by researchers such as Keulegan [17] to Kouwen and Li [18], and most recently, Fathi-Maghadam and Kouwen [9], has shown that the drag coefficient for flexible objects such as plants varies with the plant type, plant shape, the bending of the plant with flow, the distortion of the plant's leaf mass with flow, and the effect of upstream plants or plant density. For flexible plants, the drag coefficient is then a function of a number of factors. It is important to note that the following analysis was developed in conjunction with the actual testing.

$$C_D = f\left(R_e, \frac{Y_O}{H}, \textit{plant type}, \textit{plant shape}, \textit{plant flexibility}, M \right)$$

3-8. Flume Testing. Tests in both the large flume and a sectional flume were conducted for a large matrix of variables including Y_O, V, plant type, plant density, plant shape, plant size, and blockage area. The runs were made in a sequence so that each variable could be evaluated by keeping the other variables constant. It was found that flow resistance or drag coefficient decreased with an increase in velocity with constant depth, plant density, etc. Flow resistance or drag coefficient decreased with an increase in depth with constant velocity, plant density, etc. Flow resistance or drag coefficient decreased with a decrease in plant density with constant velocity, depth, etc. Flow resistance or drag coefficient decreased with an increase in plant flexibility or distortion with constant velocity, plant density, plant height, plant blockage, etc. Flow resistance or drag coefficient decreased with an increase in plant elasticity with constant velocity, plant density, plant height, plant blockage, etc.

3-9. Dimensional Parameters. Sectional flume tests of individual plants were conducted to measure the drag force F_D for different plants. This testing has shown that F_D and C_D are a function of V_P, E, D_S, H, H', and W, where D_S = the stem diameter and H' = the undeflected height of the leaf mass. Therefore, it has been proposed that V^*/V or C_D in a vegetated channel should be a function of the parameters (F_I/F_B, Y/H, MA, R_e). The parameter F_I/F_B is the ratio of the inertial force to the bending force or stiffness of an individual plant. The parameter Y/H is the ratio of flow over the top of a plant, the parameter MA is the ratio of total plant blockage to bed area, and R_e is the Reynold's number based on hydraulic radius. The parameters Y/H, MA, and R_e can be thought of as corrections to the mean velocity.

$$\frac{V^*}{V} \text{ or } C_D = f\left(\frac{F_I}{F_B}, \frac{Y}{H}, MA, R_E \right) \tag{3-20}$$

The form of the inertia to stiffness ratio used in this study is:

$$\frac{F_I}{F_B} = \frac{\rho V^2 A}{E A_S} \tag{3-16}$$

where A is the blockage area of an individual plant, E is the plant stiffness of a single stem of an individual plant, V is the mean or average flow velocity, and A_S is the total cross sectional area of the stems of an individual plant. A_S is determined from the stem diameter D_S, which is measured at a height of H/4 from the base of the plant.

3-10. Plant Stiffness. The relative plant stiffness modulus E is determined using a simple cantilever beam theory (Equation 3-17) and by measuring the force F_{45} required to bend the plant at an angle of 45 degrees. This bending angle is measured from the base of the plant stem to the center of the leaf mass. The bending force F_{45} is applied and measured at the center of the leaf mass, 45 degrees occurs when the center of the leaf mass moves horizontally equal to the vertical height to the center of the leaf mass, and I is the second area moment of inertia calculated for a circular shape. The stem diameter D_S (where $I = \pi D_S^4/64$) is measured at a height of H/4 above the ground. It is important to note that the plant stiffness E determined by this method is a relative measure of plant stiffness used to facilitate field applications.

$$E = \frac{F_{45} H^2}{3 I} \tag{3-17}$$

3-11. Modulus of Elasticity. Recent work by Fathi-Maghadam and Kouwen [9] suggests a methodology by which to determine the actual modulus of elasticity. When dealing with vegetation resistance, however, what is important is a measure of the plant's ability to bend and deform with the flow. The modulus of elasticity E is a measure of stiffness, but actually bending the plant provides a measure of both stiffness and flexibility. The methodology proposed in this study (Section 4-7) provides a simple method that is easily accomplished in the field. It also provides a direct measure of the plant's ability to deform.

3-12. Reynold's Number. The Reynold's number R_E used in this study is based on the hydraulic radius R_h.

$$R_E = \frac{V\,R_h}{\nu} \tag{3-18}$$

CHAPTER 4

TEST SETUP AND PROCEDURE

Section I. Introduction

4-1. General. Two flumes were used for the plant tests of this study. The large flume at the hydraulics laboratory was used for multiple plant tests. The large flume is an 8-foot wide by 6-foot deep by 500-foot long rectangular flume with a horizontal floor. A sectional flume was constructed from one of the laboratory's 3-foot wide by 3-foot deep return flow channels.

Section II. Test Plants and Dimensions

4-2. Description. There were 13 different groups of plants tested in the large laboratory flume and 10 groups of plants tested in the sectional flume. All of the plants tested were broadleaf deciduous, woody vegetation, and found in most USDA zones. The plants tested in the larger flume were placed in staggered rows along the 50-foot length of the test section. The spacing selected for the plants was based on the typical spacing [16] of 1½ to 2 plant diameters for emergent plants. The plants tested in the sectional flume were placed in a single row of four to five plants along the centerline of the flume. A single plant was instrumented for determining drag force in each flume. The test plant in the larger flume was located in the center of the 50-foot by 8-foot test section. The test plant for the sectional flume was the last plant, with four plants located upstream.

4-3. Plant Preparation. With the exception of the plants used to test for drag forces, all of the plants in the large flume were placed intact, with root structure, into one-gallon pots that were attached to the floor. The plants were anchored through the pots by wiring the plant stem to a section of chain link fencing placed flat on the concrete bottom of the flume. The test plants in the sectional flume and the drag force plant of the larger flume were cantilevered into the test platform and load cell. The roots of the cantilevered plants had to be removed.

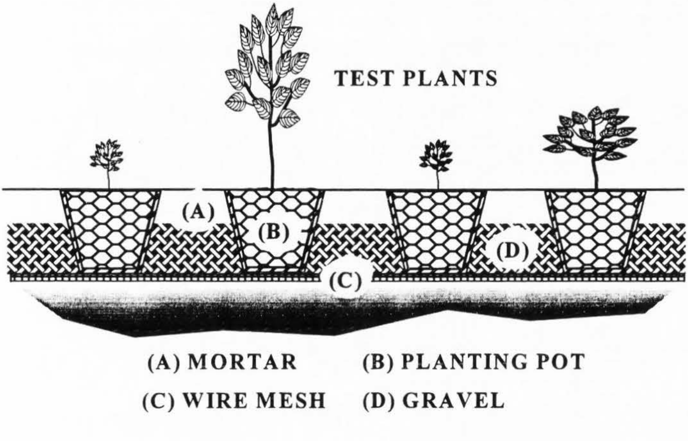

Figure 4-1. Setup for test Plants

4-4. Plants Tested. The 13 plants tested in the large flume were:

1) 20-inch Yellow Twig Dogwood (Cornus stolonifera Flaviramea)

2) 28-inch Berried Elderberry (Sambucus Racemosa)

3) 8-inch Purpleleaf Euonymus (Euonymus Fortunei Colorata)

4) 38-inch Red Twig Dogwood (Cornus Sericea)

5) 28-inch Service Berry (Amelanchier)

6) 28-inch Yellow Twig Dogwood (Cornus stolonifera flaviramea)

7) 38-inch Mulefat (Baccharis glutinosa)

8) 30-inch Alder (Alnus incana)

9) 38-inch Valley Elderberry (Sambucus mexicana)

10) 60-inch Salt Cedar (Tamarix spp.)

11) 48-inch Black Willow (Salix nigra)

12) 24-inch Red Willow (Salix spp.)

13) 60-inch Mountain (Cocotte/Black) Willow (Salix monticola).

The 10 plants tested in the sectional flume were:

1) 20-inch Yellow Twig Dogwood (Cornus Stolonifera Flaviramea)

2) 8-inch Purpleleaf Euonymus (Euonymus Fortunei Colorata)

3) 22-inch Arctic Blue Willow (Salix Purpurea Nana)

4) 28-inch Maple (Acer Platenoides)

5) 32-inch Common Privet (Ligustrum Vulgare)

6) 21-inch Blue Elderberry (Sambucus Canadensis)

7) 36-inch French Pink Pussywillow (Salix Caprea Pendula)

8) 36-inch Sycamore (Platenus Acer Ifolia)

9) 29-inch Western Sand Cherry (Prunis Besseyi)

10) 30-inch Staghorn Sumac (Rhus Typhina).

4-5. Plant Dimensions. Table 4-1 shows the average dimensions and plant characteristics of the plants tested in the large flume. Table 4-2 shows the average dimensions and characteristics of the plants tested for drag force in the sectional flume. Figures 4-2, 4-3, and 4-4 show the dimensional characteristics of the plants tested. The range of heights of individual plants varied from the average height characteristics in Table 4-1 with a variation of 3 inches; the plant widths varied by 4 inches, and the diameters of the stems varied by one sixteenth of an inch.

4-6. Definitions of Plant Characteristics. The following are the definitions of the plant characteristics and dimensions used in this study:

A is the blockage area of a plant projected to the flow direction (ft^2),

A can be approximated by H' x W.

A_S is the total cross-sectional area of the stems of the plant at H/4 from the base (ft^2).

D_S is the stem diameter of an individual stem measured at H/4 above the bed (ft).

E is a relative measure of plant stiffness (lb/ft^2).

F_{45} is the force to bend a plant stem by 45 degrees (lb).

H is the height of the plant (from bed to the top of the plant) (ft).

TABLE 4-1. Plant Characteristics and Dimensions Tested in the Large Flume

Plant Type	Height H ft	Width W ft	Stem Dia D ft	Eff Height H' ft	Blockage A ft²	Stems #	Stem Area As ft²	Elasticity E lb/ft²
Small								
Dogwoods	1.667	0.750	0.031	1.083	0.813	1	0.001	6.70e+06
Elderberry	2.333	1.167	0.031	1.667	1.944	1	0.001	1.10e+06
Euonymus	0.667	0.833	0.021	0.667	0.556	2	0.001	8.64e+06
Large								
Dogwoods	3.167	1.583	0.083	2.500	3.958	2	0.011	2.13e+07
Service								
Berry	2.333	0.583	0.021	1.667	0.972	6	0.002	9.99e+07
Medium								
Dogwoods	2.396	0.833	0.031	2.000	1.667	2	0.002	6.25e+07
Mulefat	3.167	0.250	0.042	1.667	0.417	1	0.001	1.24e+07
Alder	2.500	0.500	0.026	2.300	1.150	1	0.001	3.55e+07
Valley								
Elderberry	3.167	2.500	0.063	3.000	7.500	2	0.006	3.44e+07
Salt Cedar	5.000	2.000	0.104	4.500	9.000	1	0.009	2.73e+07
Black								
Willow (tall)	4.000	1.000	0.063	4.000	4.000	1	0.003	3.13e+06
Red Willow								
(med)	2.000	0.500	0.031	2.000	1.000	1	0.001	9.40e+06
Mountain								
Willow	5.000	3.000	0.084	4.000	12.000	4	0.022	7.13e+06

TABLE 4-2. Dimensions and Characteristics of Plants Tested for Drag Force

Plant/Runs	H(cm)	W_p(cm)	D_S(cm)	H' (cm)	E (N/m^2)	# Leaves	Leaf Size
Dogwood	50.8	22.9	0.95	33.0	2.1466E8	50	7.62 cm long 1.27 cm wide
Euonymus	20.3	25.4	0.635 2ea.	20.3	4.1363E8	90	5.08 cm long 1.27 cm wide
Arctic Blue Willow	55.9	30.5	1.27	50.8	1.1932E8	140	5.08 cm long 1.27 cm wide
Norway Maple	71.1	30.5	1.27	30.5	1.9118E9	140	5.08 cm long 1.27 cm wide
Common Privet	81.3	25.4	1.27	68.6	3.9404E8	275	3.30 cm long 0.95 cm wide
Blue Elderberry	53.3	45.7	2.54	40.6	2.6296E7	175	6.35 cm long 1.91 cm wide
Pink Pussy willow	91.4	25.4	1.91	25.4	1.1063E8	90	3.81 cm long 1.27 cm wide
Sycamore	91.4	20.3	1.02	83.8	2.7474E9	23	15.24 cm long 15.24 cm wide
Western Sand Cherry	73.7	15.24	0.85	50.8	2.8779E9	100	5.08 cm long 2.54 cm wide
Staghorn Sumac	76.2	25.4	1.27	30.48	5.0829E8	140	5.08 cm long 2.54 cm wide

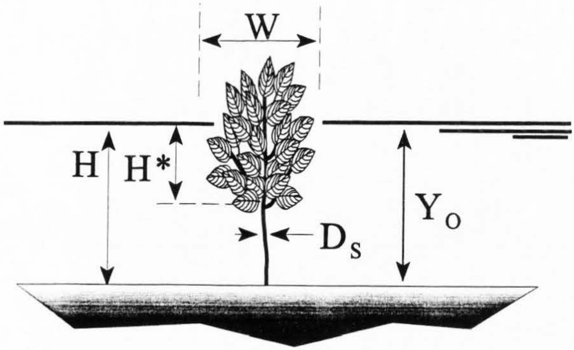

Figure 4-2. Plant Dimensions for Plants in Partially Submerged Flow

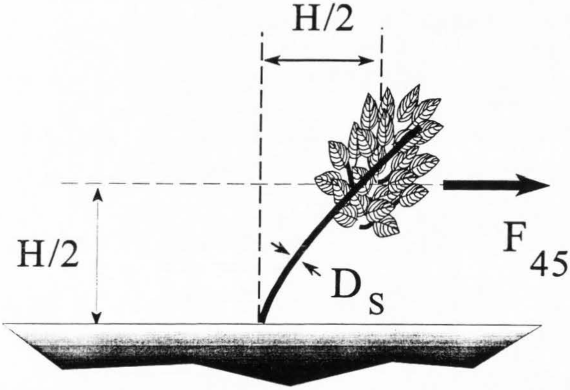

Figure 4-3. Plant Dimensions for Determining Stiffness

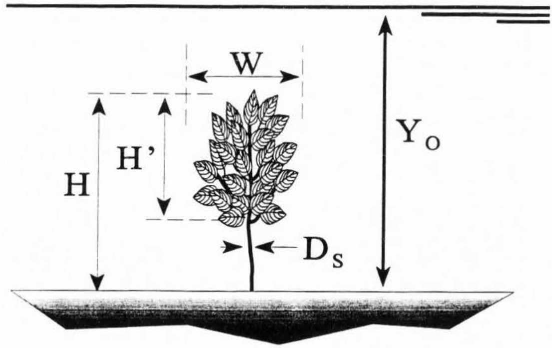

Figure 4-4. Plant Dimensions for Submerged Flow

H' is the height of the leaf mass (the vertical distance of the leaf mass) (ft).

*H** is the effective height of the leaf mass (the submerged height of the leaf mass) (ft).

I is the area moment of inertia of the stem at H/4 from the base of the plant (ft^4).

M is the plant density, number of plants per unit area (number per ft^2).

Y_O is the flow depth above the bed of the channel (ft).

W is the width of the leaf mass of the plant (ft).

4-7. Plant Stiffness. Plant stiffness is one of the biomechanical plant characteristics used in this study. The relative plant stiffness *E* used in this study closely approximates the modulus of elasticity of the stem (an average stem for multiple stem plants), which is calculated by measuring the horizontal force, F_{45}, necessary to bend the plant 45 degrees.

The force is applied (Figure 4-3) half way up, $H/2$, the stem of the plant, and the stem is pulled, $H/2$, horizontally. The modulus is calculated using Equation 4-1, where I is the second area moment of inertia.

$$E = \frac{F_{45}\, H^2}{3\, I} \quad where\ I = \frac{\pi\, D_S^{\,4}}{64} \tag{4-1}$$

It is important to note that the above method quantifies only the plant stiffness and is not a true measure of the modulus of elasticity.

4-8. Plant Density. M is the plant density in number of plants per unit area. M should not be confused with the M used by other researchers [19] to designate a relative plant density of number of plants /m² divided by 1 plant /m².

4-9. Cross-Sectional Area. The cross-sectional area, A_S, of the plant stems is used to calculate plant stiffness. The cross-sectional area is the total cross sectional area of all the stems of an individual plant. The area A_S and the stem diameter D_S are measured at a distance of $H/4$ from the bed.

Section III. Large Flume Setup

4-10. General. The concrete floor, under the test section, of the large flume (Figure 4-5) was covered with a layer of chain link fence, which extended across the width of the channel and along 110 feet of the flume. The fencing was necessary so that each individual plant could be anchored, by wire, to prevent its removal by the force of flowing water. The upstream end of the fencing was attached to a beam fixed to the bottom of the flume. The fence also helped stabilize the test bed and prevent lateral movement of the test bed during testing. The test setup for Phase II had a total of 158 one-gallon plant containers placed on 18-inch centers (with alternating rows of four and five containers per row) and anchored to the floor and fencing. A gravel bed with mortar cap (Figure 4-1) was placed and compacted in place on top of the chain link fence and around the plant containers. Phase I testing, in 1994, used a similar setup with a compacted clay top instead of the mortar top used in Phase II. The plant containers had several large drain holes, and the gravel layer then drained water away from the plants and plant containers. Plant containers were not used for the Phase I testing. The test section was located in the large flume so that the 24-foot view section of the flume's west wall was adjacent to the downstream reach of the test section.

4-11. Upstream Velocity Profile. The test reach had a length of over 50 feet (with a maximum of 158 test plants), and had additional lengths of roughened bed upstream and downstream of the test reach. Cement blocks were placed on the approach and trailing beds to create a turbulent layer and to establish a fully developed velocity distribution before and after the test reach.

4-12. Downstream Control. At the downstream end of the clay bed, stop logs were inserted into the flume and removed as necessary to slowly fill the flume. This was done

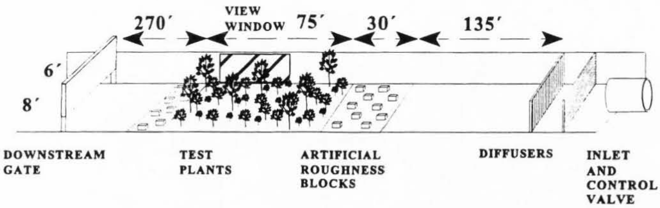

Figure 4-5. Sketch of the Large Flume

to protect the test plants during filling. At the downstream end of the flume, 300 feet downstream of the test section, a gate was used to control flow depth. A second set of stop logs was later placed downstream to also control the flow depth and to decrease the time necessary to establish steady flow after each flow change.

4-13. Water Supply. Water entered the upstream end of the flume, 165 feet upstream of the test section, from a 48-inch diameter pipe. A remote-controlled butterfly valve in the 48-inch pipeline was used to control the flow rate. A sonic meter was used to measure the flow rate in the 48-inch pipeline. A series of vertical and horizontal distribution vanes were placed downstream of the 48-inch inlet pipe to dissipate the jet from the pipe exit.

4-14. Depth and Velocity Measurements. To take depth and velocity measurements, a wheeled platform that moved on tracks adjacent to the flume sides, was positioned at 5-foot intervals of length to facilitate measurements. Water surface elevations were measured with the help of a stationary transit and a measuring rod. Flow velocities were taken with a Marsh McBirney Model 201 Portable Water Current Meter. Depth and water surface elevations were taken along the centerline of the flume. Velocity measurements were made at depth intervals of 3 inches for a vertical traverse at the middle of the test section and just upstream of the test plant used to measure drag force.

4-15. Measuring Drag Force. A single plant, in the centerline of the flume, and at station 0+25 (from the start of the plants), was selected as the test plant to determine drag force. An average sized test plant was selected and inserted into a platform to measure drag force. The test platform was a shallow metal box with ball bearings in the bottom and a metal plate resting upon the ball bearings. The test plant, with its roots removed, was attached and cantilevered from the plate. A load cell was then attached to the tail end of the plate to measure the drag force on the plant, as a compression force. By using a Vishay Instrument Model P-350 Strain Indicator, the drag force produced by the individual test plant could be determined. A specially built strain gauge was used in compression and attached to the strain indicator. The gauge was protected with a silicon sealant. The same load cell was used in both the large and sectional flume. The platform (see Section 4-26) was covered with a section of drain cloth to prevent soil from interfering with the ball bearings and movement of the plate. The platform was covered with a plastic lid to prevent friction drag on the load platform. Springs were used to position the plate within the platform's shallow box. To help eliminate buoyancy effects, the flume was filled with stationary water and the strain gage was zeroed at the start of each series of runs. The sensitivity of the strain gage was 200 microinches per inch per pound. Measurements were taken to the nearest microinch.

Section IV. Procedures For Resistance Tests

4-16. Test Bed Preparation. Prior to beginning each series of tests, the test bed was leveled and a layer of topsoil placed and compacted on top of the clay bed for Phase I testing. The mortar cap used in Phase II did not require maintenance and leveling for each series of runs. The test plants were then placed in the test flume just prior to testing. The flume was slowly filled with water with the stop logs in place and the downstream gate closed. With the flume filled and no flow, the strain gage for drag force was zeroed. Flow and depth were controlled with the downstream gate and the 48-inch inlet butterfly valve. Time was allowed for the flume to reach equilibrium before beginning each test run.

4-17. Description of Test Runs. Typically, nine test runs were made for each test series. The first three runs were made at high depths, with the flume nearly full, and at three different velocities. The next three runs were made at a medium depth, and the last three runs were made at a low depth. The test plants were usually submerged, even at low depths, because the flow forces were adequate to bend the plants with the flow. Some tests (for the larger plants) were conducted with the plants partially submerged.

4-18. Measurements Taken. The first measurements taken for each test were the water surface elevations at 5-foot intervals along the centerline of the test section. Velocity measurements were taken next. Velocity measurements were taken at 3-inch intervals of depth at station 0+25. The local velocity at the plant (plant approach velocity) was measured 2 inches from the upstream undisturbed position of the leaf mass of the test plant used to measure drag force. The plant approach velocity was measured 2 inches upstream of the test plant to avoid making a measurement in a possible stagnation region of the upstream face of the plant. Measurements taken in the plant mass and at the upstream face of the plant were inconclusive because of the interference of individual leaves, but the measurements did show that there was still substantial velocity and flow through the plant mass and through the wake region. The strain on the load cell was measured for each test run. As the depths and velocities were varied, the test plants and soil were observed through the view window for soil movement, plant distortion, and plant failure.

4-19. Calculating Backwater Curves. The procedure to calculate the Manning's coefficient *n* for the plant roughness involved an initial estimate of a total Manning's roughness coefficient to best fit the gradually varied backwater curve of water surface elevations along the test section. The gradually varied backwater curve was the result of the energy loss due to the flow resistance of the vegetation and the roughness of the test bed and flume walls. Equation 4-2 was used to fit the backwater curve.

$$\frac{dy}{dx} = \left(\frac{S_o - S_f}{1 - F_r^{\,2}} \right) \tag{4-2}$$

where dy/dx is the unit change in slope of the water surface, S_o is the slope of the bed, S_f is the slope of the energy line, and F_r is the Froude number. S_f is calculated from

Manning's equation (Equation 2-1) for the estimate of Manning's n, the mean velocity V, calculated from continuity, and the hydraulic radius R_h. The Froude number was calculated from Equation 4-3.

$$F_r = \frac{V}{\sqrt{g \cdot R_h}} \tag{4-3}$$

4-20. Calculating Manning's n. The composite Manning's n value was then iteratively solved using a trial-and-error process until the shape of the backwater curve predicted by Equation 4-2 was the same as the measured curve of the actual water surface. Figure 4-6

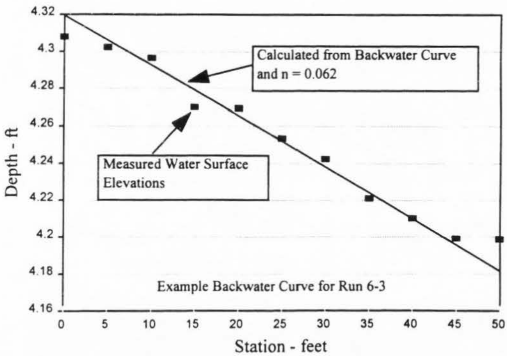

Figure 4-6. Fit of a Backwater Curve to Determine n

is an example of the backwater curve fit for a test run with a composite Manning's n of 0.062.

4-21. Determining Bed Roughness and Plant Resistance. From the composite Manning's n, the value of n_b for the bed roughness and plant roughness was determined. This was done through a number of steps. First, the total n determined by the method in Section 4-20 was converted to a Darcy-Weisbach friction factor, f, by Equation 4-4.

$$f^2 = \frac{n\sqrt{8g}}{K_n \cdot R_h^{1/6}} \tag{4-4}$$

The coefficient of friction for the bed and plants, f_b, was determined using a correction for the effects of the flume walls for a rectangular channel. The coefficient of friction for the walls, f_w, was determined from Equation 4-5 and regressed for this study to fit the correction figure presented in the ASCE Manual 54 [3].

$$f_w = 0.274\left(\frac{R_E}{f}\right)^{-0.175} \tag{4-5}$$

where R_E is the Reynold's number. Equation 4-5 was a taken from a chart found in the ASCE Manual 54 [3]. The friction factor for the bed, f_b, was then calculated with Equation 4-6.

$$f_b = f + \frac{2\,Y_O}{b}\left(f - f_w\right) \qquad (4\text{-}6)$$

where b is the width of the channel and Y_O is the flow depth. Manning's roughness coefficient for the bed roughness and plant roughness was calculated using the hydraulic radius R_b as determined by Equation 4-7.

$$\frac{R_b}{f_b} = \frac{R_h}{f} \qquad (4\text{-}7)$$

where R_b is the hydraulic radius for the bed and plants and R_h is the gross measured hydraulic radius. Equations 4-6 and 4-7 are from the ASCE Manual 54 [3] on side wall corrections. Equations 4-6 and 4-7 are from the ASCE Manual 54 [3] on side wall corrections. R_b was then substituted into Manning's equation (Equation 2-1). Finally, the Manning's coefficient n_b for the bed roughness and vegetation was calculated. The resulting coefficient was a combined roughness for the bed and vegetation.

4-22. Calculating Net Resistance. The coefficient n_b is the roughness of both the bed roughness and the vegetation. By using Cowan's approach [7], Equation 4-8 can be used to calculate the roughness coefficient n_{veg} for the net roughness of the vegetation.

$$n_{veg} = n_b - n_{base} \qquad (4\text{-}8)$$

where n_{veg} is the Manning's coefficient for vegetation; n_b is the bed and vegetation roughness; and n_{base} is the base value of only the bed roughness. The value for n_{base} was determined by testing only the soil and mortar base, without vegetation. However, this approach was not used for the final analysis because the value for n_{base} was found to vary once the vegetation was in place.

Section V. Sectional Flume Test Setup

4-23. Description. A smaller sectional flume was used to study the drag forces developed on single plants. The tests were carried out in a horizontal 3-foot wide by 3-foot high smooth sided steel flume. To produce higher velocities, a false plywood wall was built in the flume, narrowing the width to 18 inches. Water was supplied by a 3-foot by 3-foot channel running perpendicular to the flume entrance. A baffle was placed at the entrance of the flume to help straighten the incoming flow. A plexiglass observation window was also installed in the side of the flume.

4-24. Flume Setup. Since the bottom of the flume consisted of smooth steel, it was necessary to devise a method by which to attach the plants. This was accomplished by building a 1½-inch thick false deck out of smooth, painted plywood. The deck was bolted through the bottom of the flume and sealed with silicon caulk. Several 1-inch holes were drilled through the plywood to the steel bottom. These holes were placed upstream of the test plant. They were designed to hold plants, which would create a flow regime around the test plant similar to that of the test plant used in the large flume testing.

4-25. Attaching the Plants. To attach the plants to the bottom, a beveled rubber grommet and wide-flanged washers were used. The roots of the plants were cut off at the base of the stem, and then the stem was inserted through the washer and into the grommet. The rubber grommet was used to protect the base of the stem. When the plant was inserted into the grommet and the grommet was compressed, the grommet acted as a cantilevered connection (see Figure 4-7). Without the grommet, the plant tended to break at the base when subjected to high velocities. The rubber would give slightly, thus allowing the plant to bend a small amount at the base rather than shear off against the sharp edges of the plywood floor. This is similar to the conditions that the plant experiences in the field with soil around its base. The wide-flanged washers had two holes, which allowed the grommet to be attached to the plywood floor with the use of screws. Since the beveled grommet was slightly larger than the holes, the screws had to draw the grommet down into the hole, compressing the rubber.

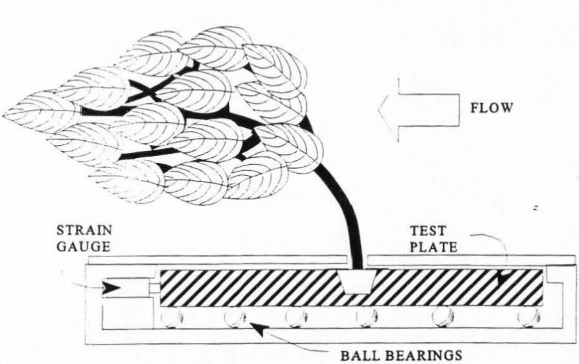

Figure 4-7. Test Setup to Measure Plant Drag

4-26. Measuring Drag Force. The test plant used to measure drag force used the same rubber grommet method, but was attached to a smooth aluminum plate rather than the plywood floor. The plate was 6 inches wide by 12 inches long and 1 inch thick. The plate provided a platform by which to measure the drag force produced on the plant. A hole was drilled into the plate and a shorter grommet had to be used because the plate was not as thick as the false deck. The plant was inserted through the washer and the grommet then screwed to the plate in the same method as the other plants. To assimilate the plate into the deck, a 6½-inch by 12½-inch rectangle was cut in the center of the floor along the centerline of the flume. Since the floor was 1½ inches thick, ½-inch diameter ball bearings were placed directly on the smooth steel floor where the plywood was removed. This allowed the plate to move smoothly on the steel deck and it also raised the top of the plate up to 1½ inches so it was exactly flush with the rest of the floor. This prevented the water from striking the face of the plate and adding to the measured drag force.

4-27. Strain Gauge. The strain gauge (0 to 10 pound range) used to measure drag force was the same gauge used in the large flume tests. The strain gauge was placed and centered directly behind the aluminum plate to measure the drag force as compression on the gauge. While the gauge was a commercially available and waterproof model, the gauge and connections were still sealed in waterproof bags. The strain gauge was temperature compensating and always zeroed in place and under water. The calibration of the gauge was checked before each test series. Elastic bands or springs were attached to both the plate and the plywood floor immediately downstream and to the sides of the plate. This held the plate firmly in contact with the strain gauge and centered in the floor cavity.

4-28. Velocity Measurements. Velocity measurements were made from a propeller-type Ott Velocity Meter. Velocity measurements were taken just upstream from the test plant used to measure drag force. Measurements were taken at different depths, and the plant velocity was taken at the depth of the center of the leaf mass.

Section VI. Procedures for Sectional Flume Drag Force Tests

4-29. Initial Measurements. Before each test series, measurements were made of plant dimensions and plant characteristics. Plant height, width, leaf size, and stem height were measured, and the number of branches, stems, and leaves was counted. The diameter of stems and branches was recorded, and the bending characteristics were also measured. The forces required to bend the plant 45 degrees and horizontal were determined. The strain gauge was first attached to the top of the plant. After the bending forces and deflection were determined there, the gauge was hooked to the center of the plant and the bending forces were again measured.

4-30. Plant and Flume Preparation. The roots of the test plant were then removed and the plant was attached to the aluminum plate. When the plate was in place, stop-logs were placed at the downstream end of the flume. The logs were placed to a height of 3 feet. This allowed the flume to be completely filled and the strain gauge set to zero to compensate for any buoyancy effects.

4-31. Downstream Control. One of the objectives of the sectional flume testing was to conduct the testing with the plants completely submerged. Because some plants did not bend far enough to completely submerge at the highest velocities and lowest flow depths, it was necessary to use stop logs to provide downstream control of the depth. When used, they were evenly spaced so that a more uniformly distributed velocity profile occurred.

4-32. Test Description. Each plant was subjected to a series of 10 runs. Each run was performed at an increasing velocity, ranging from approximately 0.25 to 8 ft/sec. During each run, the velocity directly upstream from the plant and the compression on the strain gauge were recorded. This velocity was taken at the centerline of the effective leaf area. As velocity increased, the velocity probe was lowered to compensate for plant bending. This insured that the velocity of each run was being recorded at the centerline. The angle that the plant deflected was determined from marks drawn on the sidewall of the flume. Videotapes were taken to allow for more detailed observation of the plants at a later time.

4-33. Leaf Removal. After the plant was subjected to 10 different velocities, all of the leaves were removed. The plant was then immediately subjected to 10 more runs. Velocity, drag, and deflection data were recorded in the same way.

CHAPTER 5

RESULTS OF THE SECTIONAL FLUME DRAG TESTS

Section I. Observations

5-1. General. The sectional flume had a large plastic view window to observe and measure plant distortion during testing. An important observation was that the plants easily bent with flow, and the leaf mass trailed downstream forming a streamlined, almost teardrop shaped profile (see Figure 4-7). The leaf mass became more streamlined with increased velocity. This observation explains the significant decrease in the roughness coefficient with velocity due to a reduction in blockage area. It is important to note that the leaf mass cannot be considered a rigid area of blockage, and that any approximation of a constant roughness coefficient to predict stage will be invalid. This can be shown by again considering the basic drag force equation, shown below as Equation 5-1.

$$F_D = \frac{\rho \ C_D \ A \ V^2}{2} \qquad (5\text{-}1)$$

5-2. Velocity vs. Drag. If the plant roughness coefficient were constant with increasing velocities, a plot of velocity versus drag force would appear as a smooth exponentially increasing curve. However, since the roughness coefficient decreases with increasing velocity, due to the plant's tendency to streamline, the plot appears linear. A typical plot of velocity versus drag is shown in Figure 5-1, and shows that the drag varies almost linearly with velocity until the plant can no longer streamline. At this point, resistance increases exponentially as would be predicted for a rigid object. Current research is attempting to catagorize various types of riparian vegetation in order to determine this critical velocity at which streamlining no longer occurs and the plant's drag coefficient becomes constant.

5-3. Important Plant Parameters. Dimensional analysis and multiple variable regression were performed on the data and plant measurements from the drag force tests. The analysis determined that the following plant variables could be used to predict drag force: plant height H, effective plant height H', total leaf area TL_A, stem diameter D_S, plant approach velocity V_P, fluid density ρ, plant stiffness E, and the area moment of inertia of the plant stem I. A complete list of all the parameters evaluated can be found in Table 5-1.

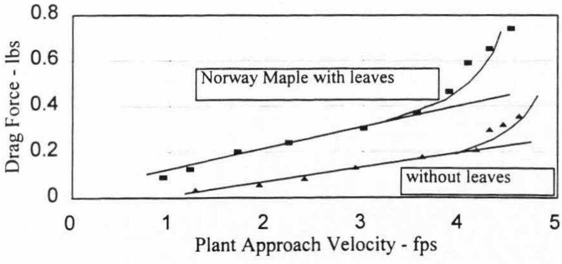

Figure 5-1. Drag Force vs. Velocity

The symbol used to designate each parameter is also included. Since a dimensional analysis was performed, Table 5-1 also includes the unit dimension for each parameter. In addition to the physical plant parameters, Table 5-1 also includes any other parameters that were measured.

TABLE 5-1. Plant Parameters Measured for Sectional Flume Tests

Parameter	Symbol	Property	Dimension
Plant Height	H	Geometric	Length (L)
Stem to First Branch	SB	Geometric	Length (L)
Number of Stems	NS	Geometric	Dimensionless
Number of Branches	NB	Geometric	Dimensionless
Number of Leaves	NL	Geometric	Dimensionless
Leaf Width	LW	Geometric	Length (L)
Leaf Length	LL	Geometric	Length (L)
Total Leaf Area	TL_A	Geometric	Length ^{2} (L^2)
Branch Diameter	BD	Geometric	Length (L)
Effective Plant Height	H'	Geometric	Length (L)
Effective Plant Width	W	Geometric	Length (L)
Velocity	V	Kinematic	Length / Time (L/T)
Density of Water	ρ	Dynamic	Mass / Length^3 (M/L^3)
Force to Pull Stem 45 Deg.	F_{45}	Biomechanical	Mass Length / Time^2 (ML/T^2)
Plant Stiffness	E	Biomechanical	Mass / [Length Time^2] ($M/(LT^2)$)
Stem Area	A_S	Geometric	Length (L^2)

5-4. Parameters Used in the Dimensional Analysis. A dimensional analysis was performed using the measured parameters. Table 5-2 shows the combination of variables used.

Section II. Results

5-5. Multiple Regression Results. Several combinations of these variables were regressed using the experimental data obtained in the small flume. The data were regressed using both a polynomial and power fit. The results of these multiple regressions can be seen in Table 5-3. It is important to note that while drag appeared to vary linearly with velocity, the regression analysis showed that V_p^2 should be used. Any linear effect of velocity is accounted for in the Reynold's number.

Table 5-2. PI Terms Used in Sectional Flume Analysis

PI Term	Variables	Description
Y	Fd / F_{45}	Ratio of Drag Force to Bending Force
X1	$E / (V_p^2 \rho)$	Ratio Bending Resistance to Inertia
X2	H / H'	Ratio of Blockage Height to Total Height
X3	$(TL_A * \rho * V_p^2) / (E * Ds^2)$	Ratio of Blockage to Bending Resistance
X4	H' / Ds	Ratio of Blockage Height to Bending Area
X5	$(H' * W) / (A_S)$	Ratio of Blockage Area to Stem Resistance Area
X6	TLA / H'^2	Leaf Blockage Function

TABLE 5-3. Results of Sectional Flume Regression Analysis

Pi Terms used in Regression	Polynomial R^2 (%)	Power Fit R^2 (%)	Polynomial Percent Error	Power Fit Percent Error
X1,X2,X3,X4,X5,X6	56%	99%	172%	18%
X1,X2,X3,X4,X6	54%	98%	98%	14%
X2,X3,X4,X5,X6	47%	99%	190%	19%
X2,X3,X4,X6	46%	89%	106%	16%
X2,X4,X6	39%	38%	100%	134%

5-6. Regression Criteria for Choosing Plant Parameters. A primary objective of this study was to develop a method by which to determine drag force based on in situ field measurements. Since this method is a field procedure, it was desirable to limit the required parameters that needed to be measured. In addition, there are several parameters that should be used due to common acceptance in the engineering community. Variables that are readily accepted include blockage area, plant stiffness, and plant height. A reasonable median was chosen based on the least number of variables that met the following criteria.

(1) The combination of variables included both geometric and biomechanical plant properties.

(2) The combination had a statistical R^2 near 90%.

(3) The resulting equation produced approximately 15% or less maximum deviation of predicted drag from the experimentally measured drag.

5-7. Resulting Drag Equations. Based on the above criteria, the following combination of variables were chosen: X2, X3, X4 and X6. The power fit was chosen because it produced a much higher R^2 and a much lower percentage of error. The regression resulted in Equation 5-2.

$$Fd = F_{45}\ [10^{1.52}\ (X2^{1.45})\ (X3^{0.8})\ (X4^{0.15})\ (X6^{0.89})] \tag{5-2}$$

Equation 5-2 is shown below with the actual variables as Equation 5-3.

$$Fd = F_{45}\ [10^{1.52}\ (\frac{H}{H'})^{1.45}\ (\frac{TLA * \rho * V_p^2}{E * D_s^2})^{0.8}\ (\frac{H'}{D_s})^{0.15}\ (\frac{H'}{TL_A^2})^{0.89}] \tag{5-3}$$

Substituting Equation 4-1 into Equation 5-3 for F_{45} yields the final form shown as Equation 5-4.

$$\frac{Fd\ H'^2}{E\ I} = 100.24\ (\frac{H}{H'})^{1.45}\ (\frac{TL_A * \rho * V_p^2}{E * D_s^2})^{0.8}\ (\frac{H'}{D_s})^{0.15}\ (\frac{H'}{TL_A^2})^{0.89} \tag{5-4}$$

5-8. Actual vs. Calculated Drag Force. A plot of actual drag forces versus drag forces calculated with Equation 5-4 can be seen in Figure 5-2.

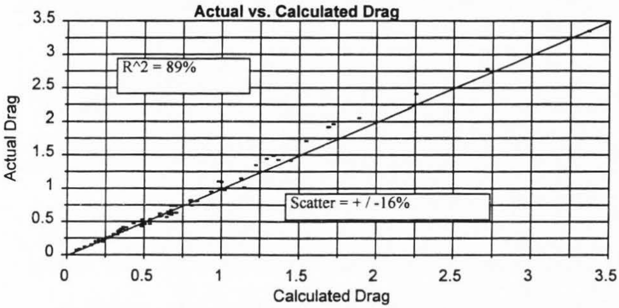

Figure 5-2. Actual vs. Calculated Drag for the Sectional Flume

CHAPTER 6

RESULTS OF THE LARGE FLUME RESISTANCE TESTS

Section I. Results of the Resistance Tests

6-1. Bed Resistance. There were eight test series for Phase I (soil bed) and 14 test series for Phase II (concrete bed) that were completed using different plant types, plant heights, plant spacings, and combinations of plant types. The first series of Phase I and the first series of Phase II were performed on only the bed, without vegetation, to determine the bed roughness. A Manning' n_{base} (corrected for wall effects) of approximately 0.02 and a V^*/V_{base} of approximately 0.095 were found for the soil bed of Phase I and also for the mortar bed of Phase II. The bed roughness values also verified the methodology used to determine resistance based on a gradually varied flow.

6-2. Summary of Results. Table 6-1 presents the results from the submerged testing of 11 different plants all conducted with uniform plant types and plant sizes for each test series. Table 6-2 presents the results from the partially submerged tests of four different plant types. All of the tests were conducted with a single plant type for each test series. Table 6-3 presents the results from the submerged tests of five different plant groups or ecosystems consisting of combinations of multiple plant types and sizes.

6-3. Velocity Profiles. Figure 6-1 is an example of the velocity profile measured for a test run. The profile demonstrates the effect of the leaf mass on the velocities. The plant approach velocity is the velocity that occurred upstream at the centerline of the leaf mass

TABLE 6-1. Summary of Results for Submerged Tests

Plant Type	Flow Depth Yo ft	Mean Velocity V fps	Energy Slope S	Plant Density M $1/ft^2$	Hydr Radius Rh ft	Reynold's Number Re	V*/V	Manning's n
Small Dogwoods	4.170	1.200	0.00053	0.498	3.944	4.30e+05	0.217	0.071
Small Dogwoods	4.120	2.000	0.00124	0.498	3.885	7.06e+05	0.197	0.065
Small Dogwoods	3.680	2.460	0.00184	0.498	3.474	7.77e+05	0.185	0.059
Small Dogwoods	3.090	1.580	0.00119	0.498	2.959	4.25e+05	0.213	0.067
Small Dogwoods	3.350	1.930	0.00140	0.498	3.185	5.59e+05	0.196	0.062
Small Dogwoods	3.440	2.260	0.00163	0.498	3.252	6.68e+05	0.183	0.058
Small Dogwoods	1.760	2.880	0.00582	0.498	1.710	4.48e+05	0.197	0.056
Small Dogwoods	2.350	3.250	0.00477	0.498	2.258	6.67e+05	0.181	0.054
Small Dogwoods	2.910	3.580	0.00418	0.498	2.766	9.00e+05	0.170	0.053
Small Dogwoods	4.450	2.510	0.00102	0.221	4.041	9.22e+05	0.145	0.048
Small Dogwoods	3.770	3.030	0.00165	0.221	3.463	9.54e+05	0.142	0.046
Small Dogwoods	1.690	3.470	0.00693	0.221	1.636	5.16e+05	0.174	0.050
Small Dogwoods	1.300	2.460	0.00496	0.221	1.382	3.09e+05	0.191	0.053
Elderberry	3.959	0.963	0.00030	0.250	3.710	3.25e+05	0.195	0.064
Elderberry	3.225	1.570	0.00063	0.250	3.003	4.29e+05	0.157	0.050
Elderberry	3.490	1.934	0.00085	0.250	3.236	5.69e+05	0.154	0.049
Elderberry	3.125	0.996	0.00043	0.250	2.971	2.69e+05	0.204	0.064
Elderberry	2.317	1.699	0.00125	0.250	2.213	3.42e+05	0.176	0.053
Elderberry	2.565	2.013	0.00110	0.250	2.404	4.40e+05	0.145	0.044
Elderberry	2.787	2.270	0.00123	0.250	2.598	5.36e+05	0.141	0.043
Elderberry	2.676	2.522	0.00167	0.250	2.510	5.75e+05	0.146	0.045
Elderberry	2.454	2.827	0.00199	0.250	2.298	5.91e+05	0.136	0.041
Elderberry	3.002	3.102	0.00191	0.250	2.778	7.83e+05	0.133	0.041
Euonymus	3.878	1.048	0.00041	1.190	3.664	3.49e+05	0.209	0.068
Euonymus	3.921	1.377	0.00055	1.190	3.671	4.60e+05	0.186	0.060
Euonymus	3.673	2.195	0.00159	1.190	3.010	6.01e+05	0.179	0.056
Euonymus	2.762	2.172	0.00225	1.190	2.651	5.23e+05	0.202	0.062
Euonymus	2.911	2.512	0.00251	1.190	2.780	6.35e+05	0.189	0.059
Euonymus	2.563	3.195	0.00408	1.190	2.452	7.12e+05	0.178	0.054
Euonymus	1.610	2.679	0.00477	1.190	1.562	3.80e+05	0.183	0.052
Euonymus	3.385	1.348	0.00053	0.529	3.169	3.88e+05	0.172	0.055
Euonymus	3.394	2.074	0.00106	0.529	3.165	5.97e+05	0.159	0.050
Euonymus	2.320	3.158	0.00332	0.529	2.205	6.33e+05	0.154	0.046

TABLE 6-1. Continued

Plant Type	Flow Depth Yo ft	Mean Velocity V fps	Energy Slope S	Plant Density M 1/ft²	Hydr Radius Rh ft	Reynold's Number Re	V*/V	Manning's n
Large Dogwoods	4.143	1.059	0.00110	0.113	4.037	3.89e+05	0.357	0.118
Large Dogwoods	4.145	1.574	0.00213	0.113	3.082	4.41e+05	0.292	0.092
Large Dogwoods	4.253	2.004	0.00266	0.113	4.116	7.50e+05	0.297	0.098
Large Dogwoods	3.085	1.139	0.00227	0.113	2.116	2.19e+05	0.345	0.102
Large Dogwoods	2.472	2.007	0.00508	0.113	2.422	4.42e+05	0.314	0.095
Large Dogwoods	2.719	3.127	0.00582	0.113	2.632	7.48e+05	0.225	0.069
Large Dogwoods	1.776	2.224	0.00833	0.113	1.747	3.53e+05	0.308	0.088
Large Dogwoods	3.067	3.154	0.00540	0.113	2.961	8.49e+05	0.227	0.071
Large Dogwoods	3.885	1.142	0.00117	0.049	3.776	3.92e+05	0.330	0.108
Large Dogwoods	2.685	1.653	0.00322	0.049	2.626	3.95e+05	0.316	0.097
Service Berry	2.265	1.148	0.00145	0.050	2.217	2.31e+05	0.280	0.084
Service Berry	3.786	1.766	0.00118	0.050	3.607	5.79e+05	0.209	0.068
Service Berry	3.173	1.844	0.00180	0.050	3.060	5.13e+05	0.228	0.072
Service Berry	2.634	2.249	0.00229	0.050	2.531	5.18e+05	0.192	0.059
Service Berry	4.182	2.257	0.00157	0.050	3.958	8.12e+05	0.198	0.065
Service Berry	3.062	2.964	0.00276	0.050	2.907	7.83e+05	0.171	0.054
Medium Dogwoods	4.455	0.477	0.00034	0.170	3.302	1.43e+05	0.401	0.128
Medium Dogwoods	4.558	1.124	0.00083	0.170	4.380	4.48e+05	0.304	0.102
Medium Dogwoods	4.136	1.994	0.00112	0.170	5.932	1.08e+06	0.232	0.082
Medium Dogwoods	3.546	3.173	0.00201	0.170	5.628	1.62e+06	0.190	0.066
Mulefat	4.668	1.339	0.00032	0.050	5.123	6.24e+05	0.172	0.059
Mulefat	4.151	2.108	0.00085	0.050	4.141	7.94e+05	0.160	0.053
Mulefat	4.474	2.375	0.00085	0.050	4.674	1.01e+06	0.151	0.051
Mulefat	3.518	2.594	0.00104	0.050	3.551	8.37e+05	0.133	0.043
Valley Elderberry	4.482	0.814	0.00102	0.160	3.523	2.61e+05	0.418	0.135
Valley Elderberry	4.365	1.400	0.00163	0.160	4.282	5.45e+05	0.339	0.113
Valley Elderberry	3.515	1.714	0.00267	0.160	3.435	5.35e+05	0.317	0.102
Valley Elderberry	2.999	2.038	0.00475	0.160	2.934	5.44e+05	0.329	0.103
Salt Cedar	4.692	1.364	0.00156	0.058	4.599	5.70e+05	0.352	0.119
Salt Cedar	4.522	1.902	0.00238	0.058	4.377	7.57e+05	0.305	0.102
Salt Cedar	3.660	2.350	0.00380	0.058	3.567	7.62e+05	0.281	0.091
Black Willow (tall)	4.646	1.028	0.00084	0.213	3.577	3.34e+05	0.303	0.098
Black Willow (tall)	4.677	1.809	0.00113	0.213	4.387	7.21e+05	0.221	0.074
Black Willow (tall)	4.554	2.503	0.00210	0.213	4.305	9.80e+05	0.216	0.072
Mountain Willow	4.351	1.379	0.00263	0.450	4.119	5.16e+05	0.428	0.142
Mountain Willow	4.639	1.725	0.00335	0.450	4.554	7.14e+05	0.406	0.137
Mountain Willow	4.194	1.967	0.00432	0.450	4.090	7.31e+05	0.383	0.127
Mountain Willow	4.534	2.936	0.00549	0.450	4.419	1.18e+06	0.301	0.101

TABLE 6-2. Summary of Results for Partially Submerged Tests

Plant Type	Flow Depth Yo ft	Mean Velocity V fps	Energy Slope S	Plant Density M $1/ft^2$	Hydr Radius Rh ft	Reynold's Number Re	V*/V	Manning's n
Large Dogwoods	2.685	1.653	0.003	0.049	2.626	3.95e+05	0.316	0.097
Salt Cedar	3.660	2.350	0.00380	0.058	3.567	7.62e+05	0.281	0.091
Salt Cedar	3.062	2.246	0.00369	0.058	2.967	6.06e+05	0.264	0.083
Salt Cedar	2.768	2.462	0.00513	0.058	2.708	6.06e+05	0.272	0.084
Salt Cedar	2.714	3.067	0.00517	0.058	2.607	7.27e+05	0.215	0.066
Black Willow	2.232	2.257	0.00175	0.213	2.088	4.28e+05	0.152	0.045
Black Willow	2.974	2.984	0.00333	0.213	2.867	7.78e+05	0.186	0.058
Black Willow	2.693	2.590	0.00326	0.213	2.603	6.13e+05	0.202	0.062
Black Willow	2.547	2.381	0.00228	0.213	2.439	5.28e+05	0.178	0.054
Mountain Willow	2.226	2.061	0.00323	0.450	2.185	4.09e+05	0.231	0.069
Mountain Willow	1.986	2.309	0.00414	0.450	1.921	4.03e+05	0.219	0.064
Mountain Willow	2.451	2.137	0.00666	0.450	2.410	4.68e+05	0.336	0.102
Mountain Willow	2.683	1.999	0.00616	0.450	2.659	4.83e+05	0.363	0.112
Mountain Willow	3.063	2.000	0.00584	0.450	3.034	5.52e+05	0.378	0.119
Mountain Willow	3.582	1.710	0.00459	0.450	3.511	5.46e+05	0.421	0.136
Mountain Willow	4.104	1.462	0.00306	0.450	4.056	5.39e+05	0.432	0.143
Mountain Willow	4.351	1.379	0.00274	0.450	4.293	5.38e+05	0.446	0.149

TABLE 6-3. Summary of Results for Multiple Plant Groups (Ecosystems)

Run	Plant density /ft²	Yo ft	avg V fps	n gross	Fd lbs	Vp fps	Sf	n net
Runs 0-1 to 0-3 were with a plain bed and no plants.								
0-2	0.000	4.334	0.687	0.016			0.00002	0.020
0-1	0.000	2.355	1.274	0.017			0.00013	0.020
0-3	0.000	4.788	1.940	0.016			0.00015	0.022
Runs 1-1 to 1-6 were with 20 each Service Berry in a 400 ft² test bed.								
1-1	0.050	2.265	1.148	0.063	3.50	1.50	0.00145	0.084
1-5	0.050	3.786	1.684	0.050	7.74	1.30	0.00132	0.076
1-2	0.050	3.173	1.844	0.050	4.99	2.00	0.00180	0.072
1-3	0.050	2.634	2.249	0.043	8.56	2.80	0.00229	0.059
1-6	0.050	4.182	2.257	0.042	9.23	1.00	0.00157	0.065
1-4	0.050	3.062	2.964	0.038	14.30	3.40	0.00276	0.054
Runs 2-1 to 2-6 were with 20 Service Berry, 68 Dogwood, and 68 Euonymus								
2-1	0.390	4.638	1.159	0.062	7.00	0.60	0.00084	0.101
2-2	0.390	4.588	1.594	0.054	8.19	0.60	0.00122	0.087
2-5	0.390	3.096	1.837	0.059	7.82	1.57	0.00253	0.085
2-3	0.390	4.222	2.161	0.052	9.98	1.60	0.00219	0.082
2-4	0.390	2.979	2.434	0.055		2.20	0.00398	0.078
2-6	0.390	2.249	2.557	0.055	11.77	3.01	0.00551	0.073
Runs 3-1 to 3-4 were with no Service Berry, 68 Dogwood, and 68 Euonymus								
3-1	0.340	4.627	1.181	0.055		0.80	0.00069	0.089
3-4	0.340	3.222	1.552	0.050			0.00126	0.072
3-2	0.340	4.152	1.761	0.048			0.00125	0.075
3-3	0.340	2.388	2.094	0.050		2.07	0.00290	0.067
Runs 4-1 to 4-4 were with no Service Berry, 68 Dogwood, and no Euonymus								
4-1	0.170	4.455	0.477	0.095			0.00034	0.154
4-2	0.170	4.558	1.124	0.063			0.00083	0.102
4-3	0.170	4.136	1.994	0.040			0.00112	0.062
4-4	0.170	3.546	3.173	0.032			0.00201	0.046
Runs 5-1 to 5-4 were with no Service Berry, no Dogwood, and 68 Euonymus								
5-1	0.170	3.921	1.377	0.037			0.00047	0.056
5-2	0.170	4.558	2.911	0.029			0.00118	0.045
5-3	0.170	1.610	2.679	0.038			0.00384	0.046
5-4	0.170	2.320	3.158	0.036			0.00342	0.047
Runs 6-1 to 6-4 were with 22 each Mulefat in a 400 ft² test bed.								
6-1	0.060	4.668	1.339	0.037	0.12	1.40	0.00040	0.059
6-2	0.060	4.151	2.108	0.035	0.22	2.30	0.00095	0.053
6-3	0.060	4.474	2.375	0.033			0.00103	0.051
6-4	0.060	3.518	2.594	0.030			0.00119	0.043

TABLE 6-3. Continued

Run	Plant density /ft²	Yo ft	avg V fps	n gross	Fd lbs	Vp fps	Sf	n net bed
Runs 7-1 to 7-4 were with 22 Mulefat and 70 Alders in a 400 ft² test bed.								
7-1	0.230	4.370	1.201	0.066	0.04		0.0011	0.106
7-2	0.230	4.411	1.496	0.052			0.001	0.083
7-3	0.230	3.766	2.048	0.047			0.0017	0.071
7-4	0.230	3.301	2.772	0.050			0.0039	0.073
Runs 8-1 to 8-6 were with 22 Mulefat and 70 Alders and 64 Valley Elderberry in a 400 ft² test bed.								
8-1	0.390	4.506	1.451	0.073	0.64	0.65	0.0019	0.119
8-2	0.390	4.397	1.714	0.070	1.28	1.10	0.0024	0.113
8-3	0.390	4.517	2.380	0.065	1.64	1.70	0.004	0.106
8-4	0.390	3.901	1.750	0.075	1.40	1.35	0.0031	0.116
8-5	0.390	3.650	1.860	0.075			0.0037	0.114
8-6	0.390	3.826	1.750	0.065	1.51	1.50	0.0024	0.100
Runs 9-1 to 9-4 were with no Mulefat and no Alders and 64 Valley Elderberry in a 400 ft² test bed.								
9-1	0.160	4.482	0.926	0.083			0.001	0.135
9-2	0.160	4.365	1.400	0.070			0.0016	0.113
9-3	0.160	3.515	1.714	0.068			0.0027	0.102
9-4	0.160	2.999	2.038	0.072			0.0048	0.103
Runs 10-1 to 10-3 were with 23 each (SUBMERGED) Salt Cedar in a 400 ft² test bed.								
10-1	0.058	4.692	1.364	0.072			0.00156	0.119
10-2	0.058	4.522	1.902	0.063			0.00238	0.102
10-3	0.058	3.660	2.350	0.060			0.00380	0.091
Runs 10-4 to 10-6 were with 23 each (PARTIALLY SUBMERGED) Salt Cedar in a 400 ft² test bed.								
10-4	0.058	3.062	2.246	0.058			0.00369	0.083
10-5	0.058	2.768	2.462	0.060			0.00513	0.084
10-6	0.058	2.714	3.067	0.048			0.00517	0.066
Runs 11-1 to 11-3 were with (SUBMERGED) 23 each Salt Cedar; 83 tall willows; and 50 short willows in a 400 ft² test bed.								
11-1	0.390	4.702	2.159	0.062	0.77	1.85	0.00290	0.102
11-2	0.390	4.330	2.604	0.062			0.00445	0.099
11-3	0.390	4.716	1.317	0.075	0.05	0.25	0.00158	0.124
Runs 11-4 to 11-7 were with (PARTIALLY SUBMERGED) 23 each Salt Cedar; 83 tall willows; and 50 short willows in a 400 ft² test bed.								
11-4	0.390	3.133	1.731	0.070			0.00314	0.102
11-5	0.390	2.583	2.120	0.065			0.00471	0.089
11-6	0.390	2.669	3.147	0.059			0.00834	0.082
11-7	0.390	2.182	2.383	0.053			0.00456	0.070

TABLE 6-3. Continued

Run	Plant density /ft²	Yo ft	avg V fps	n gross	Fd lbs	Vp fps	Sf	n net bed
Runs 12-1 to 12-3 were with (SUBMERGED) 83 tall willows; and 50 short willows in a 400 ft² test bed.								
12-1	0.333	4.646	1.162	0.060			0.00079	0.098
12-2	0.333	4.677	1.809	0.046			0.00113	0.074
12-3	0.333	4.554	2.503	0.045			0.00210	0.072
Runs 12-4 to 12-7 were with (PARTIALLY SUBMERGED) 83 tall willows; and 50 short willows in a 400 ft² test bed.								
12-4	0.333	2.974	2.984	0.041			0.00333	0.058
12-5	0.333	2.693	2.590	0.045			0.00326	0.062
12-6	0.333	2.547	2.381	0.040			0.00228	0.054
12-7	0.333	2.232	2.257	0.035			0.00175	0.045
Runs 13-1 to 13-8 were with 36 mountain willows (5 stems each) (PARTIALLY SUBMERGED) in a 400 ft² test bed.								
13-1	0.450	2.226	2.061	0.052			0.00323	0.069
13-2	0.450	1.986	2.309	0.050			0.00414	0.064
13-3	0.450	2.451	2.137	0.075			0.00666	0.102
13-4	0.450	2.683	1.999	0.080			0.00616	0.112
13-5	0.450	3.063	2.000	0.082			0.00584	0.119
13-6	0.450	3.582	1.710	0.090			0.00459	0.136
13-7	0.450	4.104	1.462	0.090			0.00306	0.143
13-8	0.450	4.351	1.379	0.092			0.00274	0.149
Runs 13-8 to 13-11 were with 36 mountain willows (5 stems each) (SUBMERGED) in a 400 ft² test bed.								
13-8	0.450	4.351	1.465	0.088			0.0028	0.142
13-9	0.450	4.639	1.725	0.083			0.0033	0.137
13-10	0.450	4.194	1.967	0.080			0.0043	0.127
13-11	0.450	4.534	2.936	0.062			0.0055	0.101
Run 14-1 was with 36 mountain willows (5 stems each) (PARTIALLY SUBMERGED) NO LEAVES								
14-1	0.450	2.869	1.952	0.066			0.0038	0.093
Run 14-2 was with 36 mountain willows (5 stems each) (SUBMERGED) in a 400 ft² test bed. NO LEAVES								
14-2	0.450	4.515	1.207	0.075			0.0014	0.122

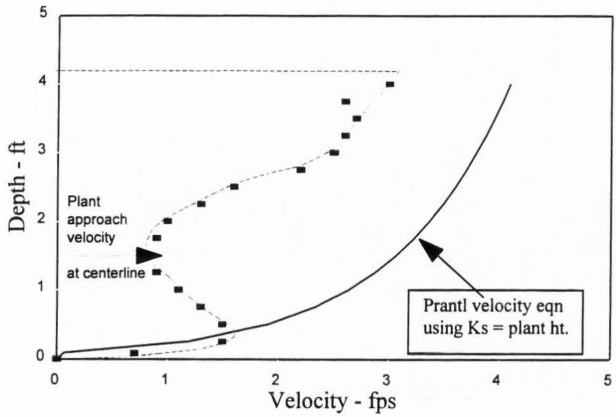

Figure 6-1. Example Velocity Profile for a Test Run of Dogwoods

of the plant. It is important to note that the velocity significantly increases below the leaf mass. The mean velocity calculated from continuity was about the same as would be predicted using the Einstein-Prandtl velocity profile equation with a roughness height equal to the height of the plant. The velocity profiles also indicate the possibility of using a linear relationship of the surface velocity to plant height to estimate the plant approach velocity.

6-4. Streamlining. The test runs were both videotaped and photographed. It was obvious that the flow resistance was influenced by the flow blockage and roughness of the leaf mass of the plants. As noted in the sectional flume, the plants easily bent with the flow, and the leaf mass trailed downstream, forming a streamlined, almost teardrop-shaped, profile. The leaf mass changed with velocity and became more streamlined with increased velocity. This observation confirms the decreasing trend of Manning's n_{veg} with velocity. It was obvious that the shrub's leaf mass cannot be considered a rigid area of blockage.

6-5. Leaf Failure. Average channel velocities from 3 to 4 fps were necessary to cause either the leaves to pull off of the plants or for the stems to break. The velocities were much greater than expected. It should also be noted that the velocities required to break stems and leaves also caused significant movement of bed material. It is likely that some, if not all, of the leaf and stem failures may have been due to impact of large bed material, e.g., gravel, that was being transported by the flow.

6-6. Scour. One of the most significant observations was that the layer of plant foliage diverted flow beneath the plants. Velocities beneath the plants were measured at levels approaching surface velocities. Measurable scour was observed beneath the plants, and even the clay bed of Phase I was eroded. The velocities were sufficient to transport and move gravel along the surface of the bed. The Euonymus plants were a ground cover type of plant, with leaves extending to the soil bed. However, with the typical spacings of the plants, there were areas of channel bottom directly exposed to flow. Measurable scour was observed in these open areas between plants for all of the tests. The test series had to be stopped for the Euonymus plants, when it was observed that the plant's root systems were failing. Local scour of the roots and bed directly upstream of the plant stems caused the removal of the bed material anchoring the plants. Only the wires attached to the plant stems kept the plants from washing downstream. Observations showed that local scour was occurring from three-dimensional flow vortices in front of the plant stems. The vortices appeared to be similar to those reported in the literature for bridge pier scour. The following Figures 6-2 through 6-6 demonstrate the effect of velocity on plant deformation, sediment transport, and scour.

Section II. Drag Test Results

6-7. Summary. Table 6-4 shows the tabulated values for the measured drag force on the test plants in the large flume for the Phase II testing. Table 6-5 summarizes the test data for the drag force measurements made in both the large and sectional flumes. A reference plant velocity of 2 fps was selected for comparison between plant types. Appendix B contains the data for the drag force tests in the sectional flume. A sample of the large flume data, as well as application examples, can be found in Appendix B. The complete large flume data set was previously published in 1996 [26].

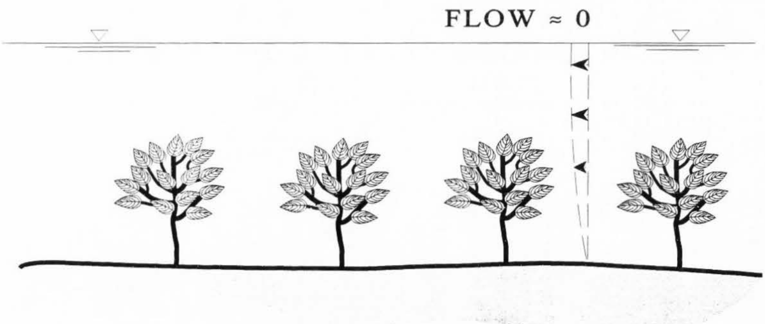

Figure 6-2. Test Plants at Zero Flow

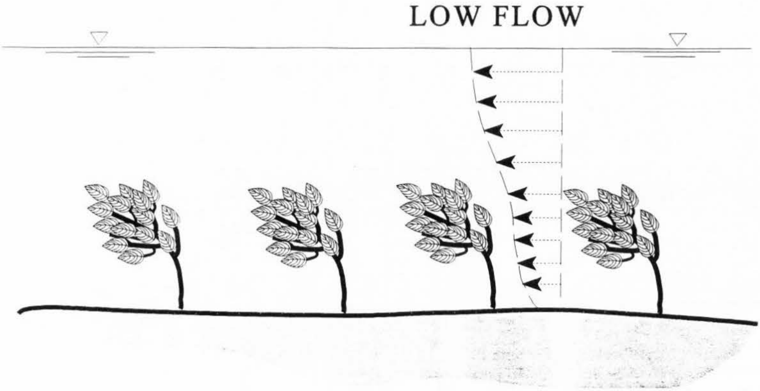

Figure 6-3. Test Plants at Low Flow

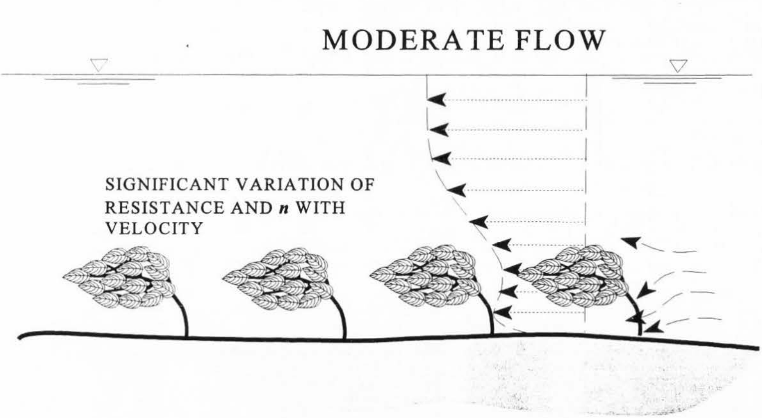

Figure 6-4. Test Plants at Moderate Flow

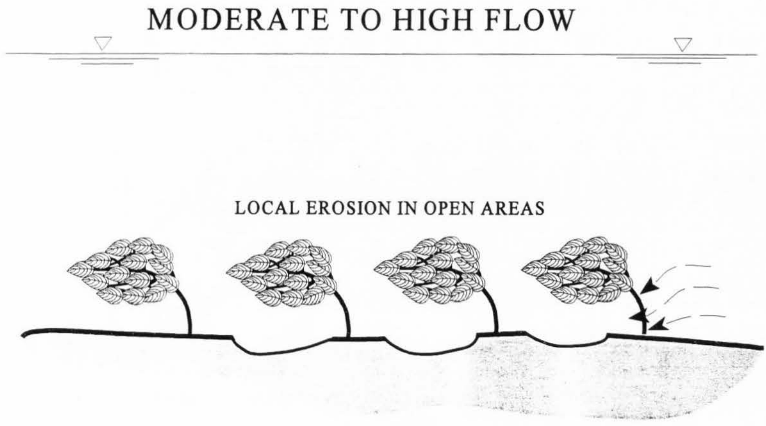

Figure 6-5. Test Plants with Local Erosion

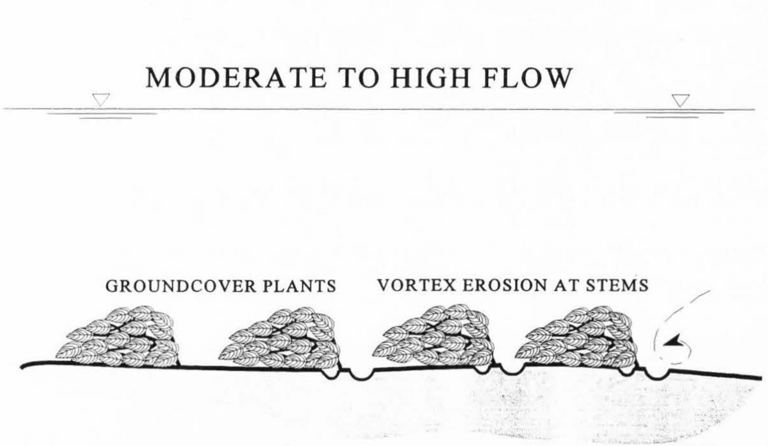

Figure 6-6. Test Plants with Stem Erosion

TABLE 6-4. Drag Force vs. Plant Approach Velocity for Large Flume Tests

Plants	Approach Velocity fps	Drag Force lbf	Plants	Approach Velocity fps	Drag Force lbf
28" Dogwoods	2.10	0.809	48" Willow	0.85	0.110
38" Mulefat	1.10	0.083	48" Willow	1.00	0.170
38" Mulefat	1.50	0.130	48" Willow	1.10	0.210
38" Mulefat	1.70	0.172	48" Willow	1.30	0.320
38" Mulefat	1.70	0.172	48" Willow	1.50	0.470
38" Mulefat	2.40	0.232	48" Willow	1.65	0.510
38" Mulefat	2.70	0.362	48" Willow	1.70	0.680
38" Mulefat	3.10	0.426	48" Willow	1.90	0.770
30" Alder	0.43	0.040	48" Willow	2.10	0.960
30" Alder	0.88	0.109	48" Willow	2.30	1.230
30" Alder	1.10	0.234	28" Service Berry	1.00	1.319
30" Alder	1.60	0.404	28" Service Berry	1.30	1.106
38" Valley Elderberry	0.40	0.294	28" Service Berry	3.40	2.043
38" Valley Elderberry	0.50	0.438	28" Service Berry	2.80	1.223
38" Valley Elderberry	0.60	0.574	28" Service Berry	2.00	0.712
38" Valley Elderberry	0.70	0.745	28" Service Berry	1.50	0.500
38" Valley Elderberry	0.80	0.989	28" Service Berry	2.10	0.808
38" Valley Elderberry	1.10	1.277			
38" Valley Elderberry	1.40	0.404			

TABLE 6-5. Summary of Phase I Drag Force Results

Plant Type	Drag Force w/ leaves	Drag Force w/o leaves	Plant Velocity
20" Dogwood* $n_{veg} = 0.037$	0.28 lbs	---	2 fps
28" Elderberry* $n_{veg} = 0.024$	0.65 lbs	---	2 fps
8" Euonymus* $n_{veg} = 0.036$	0.20 lbs	---	2 fps
38" Red Twig Dogwood* $n_{veg} = 0.052$	3.55 lbs	---	2 fps
Dogwood (series 1)	0.21 lbs	---	2 fps
Dogwood (series 2)	0.22 lbs	0.16 lbs	2 fps
Dogwood (series 3)	0.26 lbs	0.14 lbs	2 fps
Arctic Blue Willow	0.40 lbs	0.18 lbs	2 fps
8" Euonymus	0.25 lbs	0.20 lbs	2 fps
Norway Maple	0.22 lbs	0.06 lbs	2 fps
Common Privet	0.63 lbs	0.30 lbs	2 fps
Blue Elderberry	0.80 lbs	0.21 lbs	2 fps
French Pink Pussywillow	0.63 lbs	0.32 lbs	2 fps
Sycamore	0.36 lbs	0.11 lbs	2 fps
Western Sand Cherry	0.13 lbs	0.07 lbs	2 fps
Staghorn Sumac	0.28 lbs	0.10 lbs	2 fps

* Data from large flume tests

6-8. Comparison of Large and Sectional Flume Results. Figure 6-7 demonstrates the repeatability of drag force measurements between the large and sectional flumes. This is important because it shows that test data from the sectional flume can be directly compared to the plants and roughness coefficients determined in the large flume tests.

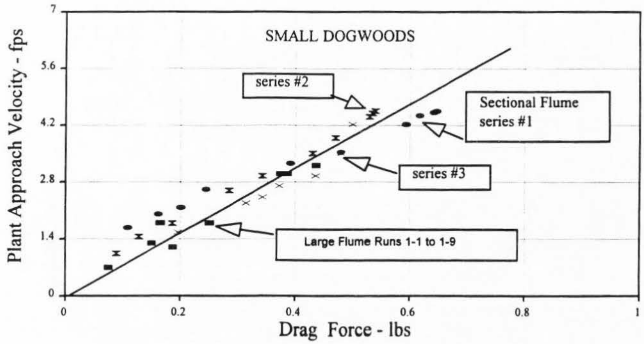

Figure 6-7. Plant Approach Velocity vs. Drag Force

Figure 6-7 also shows a linear relationship between drag force and plant velocity. Test data from four different Dogwood plants are included in Figure 6-7. It is important to note because the plants deformed or changed shape with an increase in velocity, the drag force varied linearly with velocity instead of velocity squared.

Section III. Resistance for Submerged Flow

6-9. Summary. Tests were made in the large flume to determine and measure the resistance of plants in submerged flow. Eleven different plants were tested at varying flow depths and velocities. The plants were tested with different densities, and five of the plants had multiple stems. All of the 71 runs were made with varying densities of the same size and type of plant. The range of data included mean flow velocities from 0.4 to 4 fps, the ratio of depth to plant height Y_0/H from 0.6 to 6, Reynold's numbers from 143,000 to 1,623,000, plant densities M from 0.05 to 1.2 plants per ft^2, plant heights H from 0.6 to 5 feet, stem diameters from 0.02 to 0.11 feet, stem numbers from 1 to 6, modulus of elasticity from $1x10^6$ to $1x10^8$ lbs/ft^2, a range of resistance V*/V from 0.13 to 0.43, and a range of resistance n from 0.04 to 0.15.

6-10. Corrected Resistance. The measured plant resistance was corrected so that the value also included the combined plant and bed roughness. The effect or roughness of the flume walls was corrected for by the procedures discussed in Sections 4-21 and 4-22. To further correct the roughness coefficients to include only plant roughness, the value of 0.02 should be subtracted from the n_b and the value of 0.095 should be subtracted from V*/V. The roughness coefficients predicted and reported in this study are then for the effects of plant and the underlying bed.

6-11. Resulting Equations. The resistance data reported in Table 6-1 was then analyzed to determine the regression of the variables of Equation 3-20. The regression analysis found that a logarithmic relationship gave a poor fit of data while a power relationship produced very good results. Equations 6-1 and 6-2 were found to fit the test data with a corrected correlation coefficient of R^2= 96% and a maximum scatter of 15% for predicted values of V*/V with measured values. A corrected correlation coefficient of R^2= 93% and a maximum scatter of 20% were found for predicted values of n with measured values. Figures 6-8 and 6-9 show the comparison of predicted roughness coefficients (Equations 6-1 and 6-2) with the measured test values. A perfect or 1:1 fit would be a straight line at 45 degrees. The equations also verify that resistance increases with

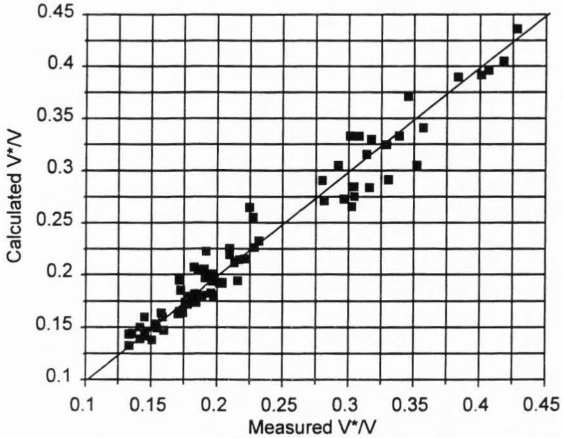

Figure 6-8. Predicted vs. Measured V*/V (Submerged Flow)

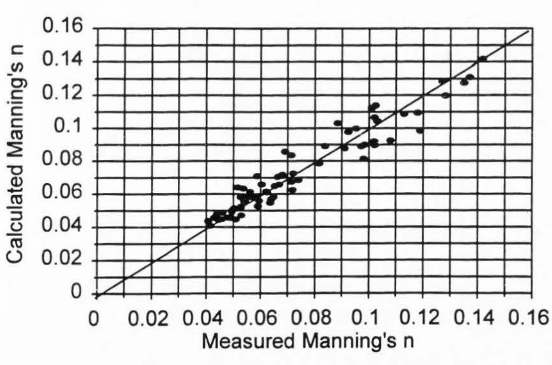

Figure 6-9. Predicted vs. Measured *n* (Submerged Flow)

increased blockage area and density, and decreases with increased depth and velocity. Appendix C contains the regression results of the various parameters evaluated.

$$\frac{V^*}{V} = 0.326 \left(\frac{E\,A_s}{\rho\, V^2 A} \right)^{0.128} \left(\frac{H}{Y_O} \right)^{0.187} (M A)^{0.182} \left(\frac{1}{R_E} \right)^{0.0828} \tag{6-1}$$

$$n = 0.039 \left(\frac{E\,A_s}{\rho\, V^2 A} \right)^{0.141} \left(\frac{H}{Y_O} \right)^{0.175} (M A)^{0.191} \left(\frac{1}{R_E} \right)^{0.0155} \tag{6-2}$$

$$C_D = 0.213 \left(\frac{E\,A_s}{\rho\, V^2 A} \right)^{0.256} \left(\frac{H}{Y_O} \right)^{0.374} \left(\frac{1}{M A} \right)^{0.637} \left(\frac{1}{R_E} \right)^{0.166} \tag{6-3}$$

6-12. Definition of Submergence. It is important to note that the plant characteristics H, A, and A_S are for undisturbed plants or for plants that have not been distorted by flow. During Phase I and Phase II testing of over 214 test runs, it was observed that since the plants bent with flow, submergence occurred at a flow depth of approximately 80% of the plant height. Equations 6-1, 6-2, and 6-3 are then for application with only submerged flow defined by $Y_O > 0.8(H)$.

6-13. Blockage Area. *A* is the effective plant area or total blockage to flow caused by the plant leaves and stems. It was found that *A* can be approximated by *H'* x *W*, where *H'* is the height of the undistorted leaf mass and *W* is the width of the undistorted leaf mass. Other relationships to evaluate blockage area were evaluated, but as long as a consistent relationship was used, the same overall regression or fit of data occurred.

6-14. Multiple Stems. Equations 6-1 and 6-2 were developed by including plants with multiple stems. The blockage area A is for an individual or average plant, the plant density is the number of plants, not stems, per unit area, and A_s is the sum of the cross-sectional area of all of the stems of an average plant.

6-15. Conclusion. The analysis of data and the regression fit of Equations 6-1 and 6-2 included many other parameters and ratios. Any of the parameters or ratios based on the methods or equations used to define a combined density and blockage area, such as the two-dimensional approaches used for heavy ground cover and grasses, did not work at all. It is also important to note that the plant characteristic of the modulus of stiffness must be used.

Section IV. Resistance for Partially Submerged Flow

6-16. Summary. Tests were made in the large flume to determine and measure the resistance of plants in partially submerged flow. Over 20 test runs were made with four different plant types. The same procedures and analysis used in Section III for submerged flow were repeated for partially submerged flow.

6-17. Resulting Equations. The resistance data reported in Table 6-2 were then analyzed to determine the regression of the variables of Equation 3-20. The regression analysis again found that a logarithmic relationship gave a poor fit of data while a power relationship had very good results. Equations 6-4 and 6-5 were found to fit the test data with a regression coefficient of R^2= 85% and a maximum scatter of 18% for predicted values of V*/V with measured values. A regression coefficient of R^2= 84% and a maximum scatter of 20% were found for predicted values of *n* with measured values.

$$\frac{V^*}{V} = 4.5x10^{-5}\left(\frac{E\,A_S}{\rho\,V^2 A*}\right)^{0.224}(MA*)^{0.0592}\left(R_E\right)^{0.530} \tag{6-4}$$

$$n = 2.2x10^{-6}\left(\frac{E\,A_S}{\rho\,V^2 A*}\right)^{0.242}(MA*)^{0.0623}\left(\frac{1}{R_E}\right)^{0.662} \tag{6-5}$$

6-18. <u>Blockage Area.</u> The blockage area in the resistance equations has been changed to an effective area, A^*, since only a portion of the leaf mass is producing blockage for partially submerged flow. The effective blockage area can be approximated by Equation 6-7 if the geometry of the plant and leaf mass have not been measured.

$$C_D = 3.624E{-}09\left(\frac{E\,A_s}{\rho\,V^2 A}\right)^{0.448}\left(\frac{1}{MA}\right)^{0.882}\left(\frac{1}{R_E}\right)^{1.061} \tag{6-6}$$

$$A^* = \left[Y_O - (H - H')\right]W \tag{6-7}$$

6-19. <u>Plant Stiffness.</u> The regression analysis again showed that plant stiffness or flexibility must be considered, and the modulus of stiffness E had to be included. The parameter Y_O/H was found to have little effect and was not used. Figure 6-10 shows a comparison or fit of Equation 6-4 with measured values of resistance.

6-20. Definition of Partial Submergence. It is important to again note that the plant characteristics *H*, *W*, A^*, and A_S are for undisturbed plants or for plants that have not been distorted by flow. During Phase I and Phase II testing of over 214 test runs, it was observed that since the plants bent with flow, submergence occurred at a flow depth of approximately 80% of the plant height. Equations 6-4 and 6-5 are then for application with only partially submerged flow defined by $Y_O < 0.8(H)$.

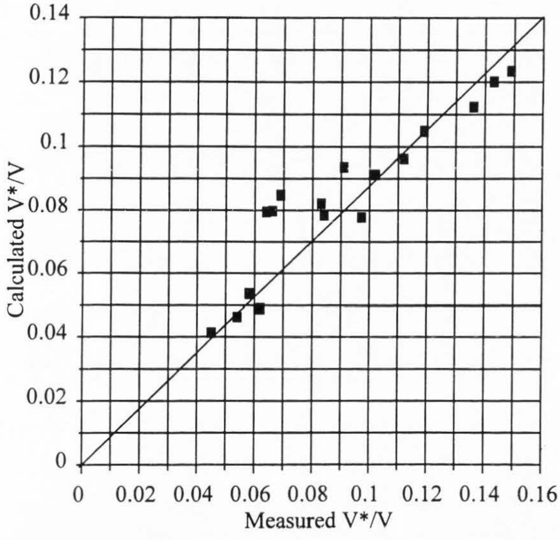

Figure 6-10. Comparison of Predicted with Measured Resistance for Partially Submerged Flow

A comparison of the equations for submerged flow and partially submerged flow showed that the equations converged on the same predicted values at the flow depth of 0.8(H).

Section V. Resistance for Multiple Plant Groupings

6-21. General. The analysis for Equations 6-1 through 6-6 of submerged and partially submerged flow used resistance data from tests of uniform sizes and types of plants. Tests were also conducted on five plant groupings or ecosystems that had several different sizes and plant types in a grouping. The results from this test have been presented in Table 6-3.

6-22. Weighted Averages. One of the objectives for the Phase II testing was to determine if the methodology developed for uniform plants could be applied to groupings of different sizes and types of plants. It was found that using a weighted average for plant characteristics and dimensions produced good correlation with the equations for submerged and partially submerged flow. For a multiple plant grouping, there are groups of similar plants within the grouping that each have a plant density and average plant dimensions associated with each group. Each group then will have a plant density M_i, a blockage area A_i or effective blockage area A^*_i, a modulus of stiffness Ei, a total plant stem area A_{Si}, a plant height H_i, and an effective plant height H'_i. A weighted average for the plant groups is then based on the ratio of M_i/M_{total}.

$$M_{total} = \sum M_i \qquad (6\text{-}8)$$

where the average characteristics are then:

$$A_{average} = \sum \left[A_i \cdot \frac{M_i}{M_{total}} \right] \qquad E_{average} = \sum \left[E_i \cdot \frac{M_i}{M_{total}} \right] \qquad A_{S\,average} = \sum \left[A_{S\,i} \cdot \frac{M_i}{M_{total}} \right]$$

$$H_{average} = \sum \left[H_i \cdot \frac{M_i}{M_{total}} \right] \qquad A*_{average} = \sum \left[A*_i \cdot \frac{M_i}{M_{total}} \right] \qquad H'_{average} = \sum \left[H'_i \cdot \frac{M_i}{M_{total}} \right]$$

6-23. Comparison of Equations. Figure 6-11 shows the application of the equations for submerged and partially submerged flow with the measured resistance for the five multiple plant groupings. The figure shows an acceptable correlation with a maximum scatter of 20%.

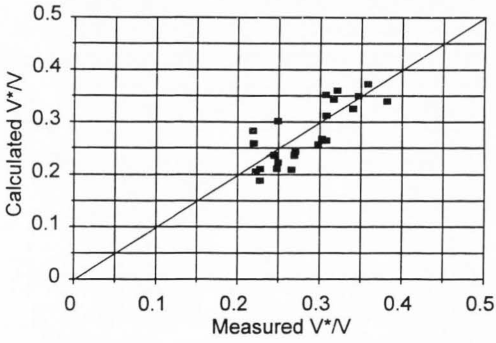

Figure 6-11. Comparison of Predicted with Measured Resistance for Multiple Plant Groupings

CHAPTER 7

CONCLUSIONS

Section I. Summary

7-1. General. The results of this study provide methodologies which can be used to quantify flow resistance caused by vegetation. Equations have been presented that are applicable to a wide variety of conditions. Methods are presented to determine *n* or V*/V for both submerged and partially submerged flow conditions, as well as multiple plant groupings. It has been shown that vegetation roughness coefficients are highly dependent upon the modulus of flexibility E, the plant density M, plant height H, flow depth Y_O and velocity V. The following equations are referenced by their original equation number.

7-2. Resistance Equations. It was found that vegetation resistance is greatly dependent upon whether or not the plants were submerged or partially submerged. For submerged vegetation, the resistance coefficient V*/V can be calculated by Equation 6-1.

$$\frac{V^*}{V} = 0.326 \left(\frac{E\,A_s}{\rho\,V^2 A} \right)^{0.128} \left(\frac{H}{Y_O} \right)^{0.187} (M A)^{0.182} \left(\frac{1}{R_E} \right)^{0.0828} \qquad (6\text{-}1)$$

For partially submerged vegetation, the resistance coefficient V*/V can be calculated by Equation 6-4.

$$\frac{V^*}{V} = 4.5x10^{-5} \left(\frac{E\,A_S}{\rho\,V^2\,A*} \right)^{0.224} (M\,A*)^{0.0592} \left(R_E\right)^{0.530} \tag{6-4}$$

7-3. Multiple Species, Non-Uniform Plants. The above Equations 6-1 and 6-4 were developed by testing both uniform and multiple plant groupings. In reference to vegetation resistance, the primary concern when dealing with homogeneous and heterogeneous vegetation is accounting for the varying degrees of height, flexibility, and blockage area among plants. This issue is addressed through the use of weighted averages to account for varying geometric and biomechanical plant properties among species. Each group will have a plant density M_i. A weighted average for the plant groups is then based on the ratio of M_i/M_{total}. The total plant density, M_{total}, is defined as the sum of densities of individual species, as shown by Equation 6-8.

$$M_{total} = \sum M_i \tag{6-8}$$

The average plant characteristics to be used with Equations 6-1 and 6-4 are then:

$$A_{average} = \sum \left[A_i \cdot \frac{M_i}{M_{total}} \right] \qquad E_{average} = \sum \left[E_i \cdot \frac{M_i}{M_{total}} \right] \qquad A_{S\,average} = \sum \left[A_{S\,i} \cdot \frac{M_i}{M_{total}} \right]$$

$$H_{average} = \sum \left[H_i \cdot \frac{M_i}{M_{total}} \right] \qquad A*_{average} = \sum \left[A*_i \cdot \frac{M_i}{M_{total}} \right] \qquad H'_{average} = \sum \left[H'_i \cdot \frac{M_i}{M_{total}} \right]$$

7-4. Correlation of Drag Force. While large-scale flume testing yields the most accurate results in determining vegetation resistance, the cost of testing may prove prohibitive for many applications. It has been shown that a reliable, lower cost alternative is to employ sectional flume testing. Equation 5-4 resulted from sectional flume testing and can be used to predict the drag force F_D associated with individual plants.

$$\frac{Fd\ H'^2}{E\ I} = 100.24\ \left(\frac{H}{H'}\right)^{1.45} \left(\frac{TL_A * \rho * V_p^2}{E * D_s^2}\right)^{0.8} \left(\frac{H'}{D_s}\right)^{0.15} \left(\frac{H'}{TL_A^2}\right)^{0.89} \qquad (5\text{-}4)$$

Equation 5-4 was developed from testing plants with and without leaves. This allows Equation 5-4 to be used to investigate the resistive effects of vegetation during an early spring runoff event or a late fall storm when the vegetation has not yet developed leaves or has lost them.

7-5. Application of Sectional Results and Equation 5-4. Care must be taken when correlating sectional flume test results to actual field conditions. The following guidelines for using Equation 5-4 are suggested.

a. Sparsely Vegetated Floodplains. If the plant density is sparse, i.e. , the plant approach velocity is expected to be approximately the same as the mean channel velocity, use Equation 5-4 to get F_D for a single plant. Equation 3-7 is then used to get C_D for a single plant. When C_D is obtained, Equation 3-14 or Equation 3-15 is then used to calculate the resistance at a given flow depth and mean velocity.

$$F_D = \frac{\rho\ C_D\ A\ V_p^2}{2} \qquad (3\text{-}7)$$

$$\frac{V*}{V} = \left(\frac{A \cdot M \cdot C_D}{2}\right)^{1/2} \tag{3-14}$$

$$n = K_n \cdot R_h^{1/6} \cdot \left(\frac{A \cdot M \cdot C_D}{2g}\right)^{1/2} \tag{3-15}$$

b. Partially Submerged. If the vegetation is expected to be partially submerged, or all of the flow is through the leaf mass, the plant approach velocity is then taken to be equal to the mean channel velocity. The approach is the same as for sparse vegetation where Equation 5-4 is used to obtain F_D for a single plant, Equation 3-7 to get C_D for a single plant, and then Equations 3-14 or 3-15 to evaluate the resistance at a given flow depth and mean velocity.

c. Use of Field Measurements. If possible, an ideal situation is to obtain actual field data that provide the plant approach velocity. If the plant approach velocity is known, Equation 5-4 is used to obtain F_D for a single plant, Equation 3-7 to get C_D for a single plant, and then Equations 3-14 or 3-15 to evaluate the resistance at a given flow depth and mean velocity.

d. Relative Resistance. An alternative method of using sectional flume models is to obtain a relative resistance value. To determine the relative resistance, sectional flume testing is employed to determine the drag force on a certain species of vegetation. This drag force is then compared to the published large flume test results. A similar plant is found from the large flume tests (similar in drag at a given velocity) and the results are scaled. For example, if a plant demonstrates twice the amount of drag as a small Dogwood, the expected resistance will be twice that which was measured for the Dogwood. The accuracy of this method has not been determined. Additional tests are needed to determine the limits of this method of relative resistance.

7-6. Blockage Area. The results of this study clearly indicate that the frontal plant blockage area should be included when determining vegetation resistance. This study also concludes that current methodology of assuming a constant roughness coefficient should be modified. Variations of this coefficient can be attributed primarily to the changing blockage area for different velocities. Flexible vegetation tends to streamline with increasing velocity, thus reducing its blockage area. While a measure of blockage area is needed, it is not possible to predict the differences in area with changes in velocity. The proposed solution to this problem is incorporating the initial blockage area with the plant's ability to deform. The initial blockage area is the effective height (H*) times the effective width (W). The effective height and width are determined by measuring the main branched area of the plant.

7-7. Plant Stiffness. The ability of plants to deform and streamline with increasing flows can be quantified by the plant's flexibility. A measure of flexibility is the modulus of elasticity. However, due to the difficulty of measuring a true modulus of elasticity, it is approximated with the plant stiffness modulus E. Many methods of measuring E have been suggested. Most methods prohibit E from being determined quickly and efficiently in the field. This study has developed an efficient and reliable field method for determining the plant stiffness E. With the aid of a small hand scale and a tape measure, Equation 4-1 allows the field investigator to quickly determine E over a large sample area for a large number of plants.

$$E = \frac{F_{45} H^2}{3 I} \tag{4-1}$$

7-8. Effects of Vegetation on Sediment Transport. Sediment transport was observed for a broad range of flows. It was found that in many cases the plants caused local vortices, which accelerated erosion around the base of the plants. Erosion and sediment transport appeared to be the worst when the vegetation was very uniform and evenly spaced with exposed soil between the plants. Uniform plant configurations where the leaf canopy was above the soil surface and of nearly equal height appeared to accelerate the flow and erosion under the plants. There are several implications to this, the first being the increase in flow under the canopy caused bottom velocities to nearly equal the velocities measured at the surface. A second and very significant implication is the fact that the velocity distribution and bed shear cannot be predicted by using commonly accepted equations for normal or typical flow distribution. Any equations or methodologies developed on the basis of normal flow distribution could then produce large errors in calculating resistance, stage discharge, or flooding. Methodologies such as sediment transport equations that are based on bed shear approximations would also produce serious errors in their predictions.

7-9. Maximum Plant Velocities. It was also noted that vegetation was able to withstand velocities of nearly 10 fps in the sectional flume, while the vegetation lost branches and leaves with velocities as low as 2-3 fps in the large flume. This can be attributed to the fact that the sectional flume used clean, sediment-free water, while the large flume had a clay bed and a large amount of sediment. The sediment-laden water caused considerably more damage to vegetation when the sediment particles struck branches and leaves. This is an important consideration when planning and specifying plants for restoration projects. While the overall effects of the sediment were noted, quantifying the results is difficult and needs further study.

7-10. Comparison with Actual Field Data. Several field studies were conducted in 1995 by Dr. Gary Freeman et al. of the Waterways Experiment Station [12]. The studies were made of the Bigwood and Henry's Fork Rivers in Idaho, and the Big Cottonwood Creek in Utah. All seven sets of flow conditions were taken with partially submerged plants. There was a good correlation (less than 15% difference) for the predicted resistance (Equations 6-4 and 6-5) with the resistance measured from the field studies. The only data set (greater than 15% difference) that had questionable results is run *BCW-cha* [12]. The measured resistance for this run was a Manning's n of 0.33, which was much larger than for other measured locations along the same stretch of the Big Cottonwood. This location also involved a very high density of plants with flood debris intermixed with the plants as compared to the other locations.

7-11. Limitations of Equations. It is important to note that the equations presented in this study were developed empirically for a limited range of data. This range of data is presented below in section 7-12. While it has been shown that the equations correlate well with the large and sectional flume data, as well as actual field data, it is unknown how accurate the results will be when applied to conditions outside of those studied. It is also important to note that the above resistance equations require an iterative solution because the channel velocity and flow depth are variables within the equations. The iterative solution then requires an initial approximation of resistance to first calculate velocity and depth. The resistance equations are then used to check and correct the initial approximation. The methodology may require a number of iterations to converge on the final velocity, depth, and resistance. The writer is currently developing software that will provide a tool by which to perform this iteration and yield results that may then be used in current software packages such as HEC-RAS.

7-12. Range of Data. The following is a summary of the range of test data obtained during this study.

a. Large Flume Data. Tests were made in the large flume to determine and measure the resistance of plants in submerged and partially submerged flow. Eleven different plants were tested at varying flow depths and velocities. The plants were tested with different densities, and five of the plants had multiple stems. Ninety test runs were made with varying densities of the same size and type of plant. Thirty-five test runs were made with five different combinations or groupings of different sizes and types of plants. The range of data included mean flow velocities from 0.4 to 4 fps, the ratio of depth to plant height Y_0/H from 0.6 to 6, Reynold's numbers from 143,000 to 1,623,000, plant densities M from 0.05 to 1.2 plants per ft^2, plant heights H from 0.6 to 5 feet, stem diameters from 0.02 to 0.11 feet, stem numbers from 1 to 6, modulus of flexibility from $1x10^6$ to $1x10^8$ lbs/ft^2, a range of resistance V^*/V from 0.13 to 0.43, and a range of resistance n from 0.04 to 0.15.

b. Sectional Flume Data. Over 200 test runs were made in the sectional flume with 10 different species of plants. The range of data included mean flow velocities from 0.9 to over 5 fps, the ratio of depth to plant height Y_0/H from 1.0 to 1.7, plant heights H from 20.3 cm to 91.4 cm, stem diameters from 0.635 to 2.54 cm, stem numbers from 1 to 2, modulus of flexibility from $2.7x10^7$ to $2.9x10^9$ N/m^2, and a range of measured drag forces from 0.03 to 3.4 lb.

7-13. Additive Resistance. It was found that Cowan's additive method, which was described in Section 2-5, is not valid for vegetated channels. The base roughness n_b is not the sum of the bottom roughness n_0 and the vegetative roughness n_4. This was verified by the fact that for many of the test runs, the velocity at the channel bottom was either very low or quite high depending on the vegetation type and configuration. This difference in velocity resulted in a different roughness value for the bed when vegetation was present than what was measured without vegetation. Based on the difference in bed roughness, this study presented the results for vegetation roughness as a composite total including both the bed and vegetation roughness.

Section II. Recommendations

7-14. General. The following is a list of suggestions for future investigations that would further enhance the applications of this study and address the limitations addressed in section 7-11.

a. Additional Types of Vegetation. Additional testing with different types of vegetation such as cedars and conifers, where the leaf structure is different from the deciduous types of plants tested in this study, would provide valuable information for northern areas such as Canada.

b. Compound Channels. This study was modeled in a single channel. Testing in a compound channel with right and left overbanks would provide much more information on boundary losses. In addition, compound channel testing would provide valuable information on velocity profiles in naturally occurring floodplains.

c. Vegetation Modeling. Sectional testing to determine the possibility and methods by which to model vegetation, especially vegetation that would be too large to fit in a small sectional flume, would be useful in providing a cost-effective method to determine resistance.

d. Flexible Vegetation and Grasses. Large flume testing of plant groups in combination with grasses would provide a more accurate model of existing conditions. This should be done in combination with sectional testing to determine the validity of sectional modeling.

e. Rigid Blockage. An application should be developed to use equations with rigid blockage such as tree trunks. This should be done to determine if the equations proposed in this study are valid by simply using very high modulus of flexibility values.

f. Field Testing. Additional field tests should be done, especially outside of the range of values tested in this study. This would help identify the limitations of the methods proposed in this study and identify the ranges on which additional testing should be focused.

g. Fluid Dynamics. An important consideration that was not investigated in this study is the effect of the fluid dynamics on the vegetation. It was noticed that the vegetation vibrated in the flow. This may be a result of the fluid turbulence around the plants or possibly a source of turbulence. This study was based on steady-state conditions, but further investigation of the effects of unsteady flow conditions on vegetation resistance would be beneficial.

REFERENCES

1. Abdelsalam, M. W., Khattab, A. F., Khalifa, A. A., and Bakry, M. F. 1992. "Flow Capacity Through Wide and Submerged Vegetal Channels," Journal of Irrigation and Drainage Engineering, ASCE, Vol 118, No. 5, pp 724 - 732.

2. Arcement, G. J. Jr., and Schneider, V. R. 1989. "Guide for Selecting Manning's Roughness Coefficients for Natural Channels and Floodplains," Water-Supply Paper No. 2339, United States Geological Survey, Denver, Colo.

3. ASCE Manual 54. 1977. "Sedimentation Engineering," Vito A. Vanoni, Ed., ASCE Task Committee, American Society of Civil Engineers, New York.

4. Barnes, H. H. 1967. "Roughness Characteristics of Natural Channels," Water-Supply Paper No. 1849, United States Geological Survey, Washington, D.C.

5. Benson, M. A., and Dalrymple, T. 1967. "General Field and Office Procedures for Indirect Office Procedures," Book 3, Chapter A1, Techniques of Water Resources Investigations of the United States Geological Survey, Washington, D.C.

6. Chow, V. T. 1959. Open-Channel Hydraulics, McGraw-Hill Book Co., New York.

7. Cowan, W. L. 1956. "Estimating Hydraulic Roughness Coefficients," Agricultural Engineering, Vol 37, No. 7, pp 473-475.

8. Dracos, T., and Hardegger, P. 1987. "Steady Uniform Flow in Prismatic Channels with Flood Plains," Journal of Hydraulic Research, Vol 25, No. 2, pp 169-185.

9. Fathi-Maghadam, M., and Kouwen, N. 1997. "Nonrigid, Nonsubmerged, Vegetative Roughness on Floodplains," Journal of Hydraulic Engineering, ASCE, Vol 123, No. 1, pp 51-58.

10. Fishenich, J. C. 1994. "Flow Resistance in Vegetated Channels; Summary of the Literature," T. R. HL-94, US Army Engineers Waterways Experiment Station, Vicksburg, Miss.

11. Fishenich, J. C. 1996. "Velocity and Resistance in Densley Vegetated Floodways," Ph.D. Dissertation, Department of Civil Engineering, Colorado State University, Fort Collins, Colo.

12. Freeman, G. E., Derrick, D., and Rahmeyer, W. J. 1996. "Vegetative Roughness in Flood Control Channels," Draft Proceedings, 1996 ASCE North American Water & Environment Congress, Anaheim, Calif.

13. Jarrett, R. D. 1984. "Hydraulics of High-Gradient Streams," Journal of Hydraulic Engineering, ASCE, Vol 110, No. HY11, pp 1519-1539.

14. Jarrett, R. D. 1985. "Determination of Roughness Coefficients for Streams in Colorado," Water-Resources Investigations Report 85-4004, United States Geological Survey, Washington, DC.

15. Jarrett, R. D. 1990. "Hydrologic and Hydraulic Research in Mountain Rivers," No. 3, Water Resources Bulletin, American Water Resources Association, Vol 26, pp 419-429.

16. Kadlec, R. H. 1990. "Overland Flow in Wetlands: Vegetation Resistance," Journal of Hydraulic Engineering, ASCE, Vol 116, No. 5, pp 691-706.

17. Keulegan, G. H. 1938. "Laws of Turbulent Flow in Open Channels," J. Res. Nat. Bureau of Standards, Vol. 21, No. 6, pp 707-741.

18. Kouwen, N., and Li, R. M. 1980 "Biomechanics of Vegetative Channel Linings," Journal of Hydraulic Engineering, ASCE, Vol 106, No. 6, pp 1085-1103.

19. Kouwen, N., and Unny, T. E. 1973. "Flexible Roughness in Open Channels," Journal of Hydraulic Engineering, ASCE, Vol 99, No. HY5, pp 713-728.

20. Li, R. M., and Shen, H. W. 1973. "The Effect of Tall Vegetation on Flow and Sediment", Journal of Hydraulics, ASCE, Vol 99, No. HY5, pp 793-815.

21. Limerinos, J. T. 1970. "Determination of the Manning Coefficient from Measured Bed Roughness in Natural Channels," Water-Supply Paper No. 1898-B, United States Geological Survey, Washington, D.C.

22. Lotter, G. K. 1933. "Considerations on Hydraulic Design of Channels with Different Roughness of Walls," Transactions, All-Union Scientific Research Institute of Hydraulic Engineering, Leningrad, Vol. 9, pp 238-241.

23. Masterman, R., and Thorne, C. R. 1992 "Predicting Influence of Bank Vegetation on Channel Capacity," Journal of Hydraulic Engineering, ASCE, Vol 118, No. 7, pp 1052-1058.

24. Petryk, S., and Bosmajian, G. 1975. "Analysis of Flow Through Vegetation," Journal of the Hydraulics Division, ASCE, Vol 101, No. HY7, pp 871-884.

25. Rahmeyer, W. J., and Werth, D. E., Jr. 1996. "The Study of Resistance and Stability of Vegetation Ecosystem Plant Groupings," Utah State University, Publication No. USU-400a&b, Utah Water Research Lab, Logan, Utah.

26. Rahmeyer, W. J., Werth, D. E., Jr., and Cleere R. B. 1994. "The Study of Resistance and Stability of Vegetation in Flood Channels," Utah State University, Publication No. USU-376, Utah Water Research Lab, Logan, Utah.

27. Ree, W. O., and Crow, F. R. 1977. "Friction Factors for Vegetated Waterways of Small Slope," United States Department of Agriculture, Agricultural Research Service, Publication No. S-151, Soil Conservation Service, Washington, D.C.

28. Richardson, E. V., Simons, D. B., Karaki, S., Mahmood, K, and Stevens, M. A. 1975. "Highways in the River Environment: Hydraulic and Environmental Design Consideration," Federal Highway Administration Training and Design Manual, Washington, D.C.

29. Thompson, G. T., and Roberson, J. A. 1976. "A Theory of Flow Resistance for Vegetated Channels," Transactions, American Society of Agricultural Engineers, Soil and Water Division, Vol. 1, pp 288-293.

APPENDICES

Appendix A

Sectional Flume Data

Plant Parameters Date - 9-9-94
Prop # - 84574 Run -

NOTE: Plant data collected with the strain gauge set in tension and held horizontal
Flume data obtained with strain gauge set in compression.
Strain Gauge Settings - HORIZONTAL IN TENSION
Gauge factor - 1.10
5 lbs = 1160 micro-inches / inch

Plant Type - Staghorn Sumac (Rhus typhina)

Plant Height (in) -	30
Stem to First Branch (in) -	18
Stem Diameter (in) -	0.456
Number of Stems -	1
Number of branches -	12

Number of leaves -	140
Leaf Thickness (in) -	0.016
Leaf Width (in) -	0.5
Leaf Length (in) -	2
Avg. Branch Diameter (in) -	0.104
Height of effective leave area (in) -	12
Width of effective leave area (in) -	10

	micro-inches/inch Around Stem	Force	With String	Force
Average force required to pull the topmost part of stem horizontal -	115	0.496	NA	NA
Average force required to pull the center of stem 45 degrees -	121	0.522	NA	NA
****** Deflection From Vertical (in) -				
Average force required to pull the center of stem horizontal -	168	0.724	NA	NA

DRAG AND VELOCITY DATA

Run #	Deflection (deg - horiz)	With Leaves Counter	Time (sec)	Strain	Without Leaves Counter	Time (sec)	Strain
1		58	30	50	58	30	12
2		77	30	72	72	30	22
3		94	30	84	76	30	25
4	60	97	30	90	90	30	40
5		102	30	96	110	30	50
6		121	30	100	120	30	55
7		131	30	108	125	30	65
8		150	30	132	141	30	93
9		155	30	140	160	30	110
10		160	30	148	173	30	122

Additional Notes -

Analysis Staghorn Sumac (Rhus typhina)

Run #	With Leaves Velocity (ft/sec)	Drag Force (lbs)	Without Leaves Velocity (ft/sec)	Drag Force (lbs)
1	1.63	0.216	1.63	0.052
2	2.15	0.310	2.01	0.095
3	2.62	0.362	2.12	0.108
4	2.70	0.388	2.51	0.172
5	2.84	0.414	3.06	0.216
6	3.37	0.431	3.34	0.237
7	3.64	0.466	3.48	0.280
8	4.17	0.569	3.92	0.401
9	4.31	0.603	4.44	0.474
10	4.44	0.638	4.80	0.526

Drag force (lbs) at 2 ft/sec = 0.283

Plant Parameters Date - 9-12-94
Prop # - 84574 Run -

NOTE: Plant data collected with the strain gauge set in tension and held horizontal
Flume data obtained with strain gauge set in compression.
Strain Gauge Settings - HORIZONTAL IN TENSION
Gauge factor 1.10
5 lbs = 1160 micro-inches / inch

Plant Type - Arctic Blue Willow (Salix purpurea nana)		Number of leaves -	700
		Leaf Thickness (in) -	0.014
Plant Height (in) -	22	Leaf Width (in) -	0.125
Stem to First Branch (in) -	2	Leaf Length (in) -	1
Stem Diameter (in) -	0.509	Avg. Branch Diameter (in) -	0.114
Number of Stems -	1	Height of effective leave area (in) -	20
Number of branches -	50	Width of effective leave area (in) -	10

***** NOTE - MULTI STEMMED PLANT ******	Around Stem (micro-inches/inch)	Force	With String	Force
Average force required to pull the topmost part of stem horizontal -	NA	NA	115	0.496
Average force required to pull the center of stem 45 degrees -	82	0.353	162	0.698
****** Deflection From Vertical (in) -				
Average force required to pull the center of stem horizontal -	154	0.664	320	1.379

DRAG AND VELOCITY DATA

Run #	Deflection (deg - horiz)	With Leaves Counter	With Leaves Time (sec)	With Leaves Strain	Without Leaves Counter	Without Leaves Time (sec)	Without Leaves Strain
1		36	30	48	51	30	30
2		47	30	67	65	30	36
3	50	64	30	85	88	30	48
4	40	77	30	100	106	30	52
5		84	30	112	126	30	63
6	20	98	30	122	153	30	80
7	0	105	30	130	168	30	92
8		107	30	134	172	30	102
9		125	30	170	178	30	108
10		158	30	214	187	30	120

Additional Notes -

Analysis Arctic Blue Willow (Salix purpurea nana)

Run #	With Leaves Velocity (ft/sec)	With Leaves Drag Force (lbs)	Without Leaves Velocity (ft/sec)	Without Leaves Drag Force (lbs)
1	1.02	0.207	1.43	0.129
2	1.32	0.289	1.82	0.155
3	1.79	0.366	2.46	0.207
4	2.15	0.431	2.95	0.224
5	2.34	0.483	3.50	0.272
6	2.73	0.526	4.25	0.345
7	2.92	0.560	4.66	0.397
8	2.98	0.578	4.77	0.440
9	3.48	0.733	4.94	0.466
10	4.39	0.922	5.19	0.517

Drag force (lbs) at 2 ft/sec = 0.404

Plant Parameters Date - 9-26-94
Prop # - 84574 Run -

NOTE: Plant data collected with the strain gauge set in tension and held horizontal
Flume data obtained with strain gauge set in compression.
Strain Gauge Settings - HORIZONTAL IN TENSION
Gauge fact 1.10
5 lbs = 1120 micro-inches / inch

Plant Type Norway Maple (Acer platenoides)

Plant Height (in) -	28	Number of leaves -	40
Stem to First Branch (in	8	Leaf Thickness (in) -	0.009
Stem Diameter (in) -	0.347	Leaf Width (in) -	3
Number of Stems -	1	Leaf Length (in) -	4
Number of branches -	3	Avg. Branch Diameter (in) -	0.146
		Height of effective leave area (in)	12
		Width of effective leave area (in)	18

	micro-inches/inch Around Stem	Force	With String	Force
Average force required to pull the topmost part of stem horizontal -	45	0.201	NA	NA
Average force required to pull the center of stem 45 degrees -	120	0.536	NA	NA
****** Deflection From Vertical (in) -	12			
Average force required to pull the center of stem horizontal -	290	1.295	NA	NA

DRAG AND VELOCITY DATA

Run #	Deflection (deg - horiz	With Leaves Counter	Time (sec)	Strain	Without Leaves Counter	Time (sec)	Strain
1	60	33	30	20	45	30	8
2	50	43	30	28	69	30	13
3	40	61	30	45	86	30	19
4		80	30	54	105	30	30
5		108	30	68	130	30	40
6		128	30	83	150	30	47
7		140	30	104	155	30	67
8		147	30	132	160	30	72
9		155	30	146	166	30	80
10		163	30	166	NA	30	NA

Additional Notes -

Analysis Norway Maple (Acer platenoides)

Run #	With Leaves Velocity (ft/sec)	Drag Force (lbs)	Without Leaves Velocity (ft/sec)	Drag Force (lbs)
1	0.94	0.089	1.27	0.036
2	1.21	0.125	1.93	0.058
3	1.71	0.201	2.40	0.085
4	2.23	0.241	2.92	0.134
5	3.01	0.304	3.61	0.179
6	3.56	0.371	4.17	0.210
7	3.89	0.464	4.31	0.299
8	4.08	0.589	4.44	0.321
9	4.31	0.652	4.61	0.357
10	4.53	0.741	NA	NA

Drag force (lbs) at 2 ft/sec = 0.223

Plant Parameters Date - 9-26-94
Prop # - 84574 Run -

NOTE: Plant data collected with the strain gauge set in tension and held horizontal
Flume data obtained with strain gauge set in compression.
Strain Gauge Settings - HORIZONTAL IN TENSION
Gauge facto 1.10
5 lbs = 1120 micro-inches / inch

Plant Type -	Western Sand Cherry (Prunis besseyi)	Number of leaves -	100
		Leaf Thickness (in) -	0.057
Plant Height (in) -	29	Leaf Width (in) -	1
Stem to First Branch (in) -	8	Leaf Length (in) -	2
Stem Diameter (in) -	0.303	Avg. Branch Diameter (in) -	0.104
Number of Stems -	1	Height of effective leave area (in) -	20
Number of branches -	7	Width of effective leave area (in) -	6

	micro-inches/inch Around Stem	Force	With String	Force
Average force required to pull the topmost part of stem horizontal -	40	0.179	NA	NA
Average force required to pull the center of stem 45 degrees -	138	0.616	NA	NA
****** Deflection From Vertical (in) -				
Average force required to pull the center of stem horizontal -	216	0.964	NA	NA

DRAG AND VELOCITY DATA

Run #	Deflection (deg - horiz)	With Leaves Counter	With Leaves Time (sec)	With Leaves Strain	Without Leaves Counter	Without Leaves Time (sec)	Without Leaves Strain
1		39	30	16	51	30	7
2		60	30	24	72	30	16
3	40	76	30	32	91	30	22
4	30	90	30	38	100	30	28
5		101	30	46	114	30	36
6	20	115	30	56	126	30	39
7		122	30	69	138	30	44
8		131	30	78	144	30	50
9		135	30	86	150	30	57
10		140	30	94	163	30	78

Additional Notes -

Analysis Western Sand Cherry (Prunis besseyi)

Run #	With Leaves Velocity (ft/sec)	With Leaves Drag Force (lbs)	Without Leaves Velocity (ft/sec)	Without Leaves Drag Force (lbs)
1	1.10	0.071	1.43	0.031
2	1.68	0.107	2.01	0.071
3	2.12	0.143	2.54	0.098
4	2.51	0.170	2.79	0.125
5	2.81	0.205	3.17	0.161
6	3.20	0.250	3.50	0.174
7	3.39	0.308	3.84	0.196
8	3.64	0.348	4.00	0.223
9	3.75	0.384	4.17	0.254
10	3.89	0.420	4.53	0.348

Drag force (lbs) at 2 ft/sec = 0.133

Plant Parameters   Date - 10-6-94
Prop # - 84574   Run -

NOTE: Plant data collected with the strain gauge set in tension and held horizontal
Flume data obtained with strain gauge set in compression.
Strain Gauge Settings - HORIZONTAL IN TENSION
Gauge fact 1.10
5 lbs = 1060 micro-inches / inch

Plant Type Common Privet (Ligustrum vulgare)

Plant Height (in) -	32
Stem to First Branch (in	0.5
Stem Diameter (in) -	0.5
Number of Stems -	1
Number of branches -	6

Number of leaves -	275
Leaf Thickness (in) -	0.011
Leaf Width (in) -	1.3
Leaf Length (in) -	0.375
Avg. Branch Diameter (in) -	0.203
Height of effective leave area (in)	27
Width of effective leave area (in)	10

	micro-inches/inch Around Stem	Force	With String	Force
Average force required to pull the topmost part of stem horizontal -	180	0.849	NA	NA
Average force required to pull the center of stem 45 degrees -	242	1.142	NA	NA
****** Deflection From Vertical (in) -				
Average force required to pull the center of stem horizontal -	295	1.392	NA	NA

DRAG AND VELOCITY DATA

Run #	Deflection (deg - horiz	With Leaves Counter	Time (sec)	Strain	Without Leaves Counter	Time (sec)	Strain
1		40	30	42	47	30	16
2		61	30	100	75	30	64
3		78	30	155	92	30	80
4		104	30	172	98	30	84
5	60	120	30	206	116	30	150
6	40	129	30	270	123	30	169
7	30	135	30	336	134	30	200
8		148	30	402	145	30	230
9		158	30	452	150	30	252
10	20	160	30	462	168	30	276

Additional Notes -

Analysis Common Privet (Ligustrum vulgare)

Run #	With Leaves Velocity (ft/sec)	Drag Force (lbs)	Without Leaves Velocity (ft/sec)	Drag Force (lbs)
1	1.13	0.198	1.32	0.075
2	1.71	0.472	2.10	0.302
3	2.18	0.731	2.57	0.377
4	2.90	0.811	2.73	0.396
5	3.34	0.972	3.23	0.708
6	3.59	1.274	3.42	0.797
7	3.75	1.585	3.73	0.943
8	4.11	1.896	4.03	1.085
9	4.39	2.132	4.17	1.189
10	4.44	2.179	4.66	1.302

Drag force (lbs) at 2 ft/sec = 0.632

Plant Parameters Date - 10-6-94
Prop # - 84574 Run -

NOTE: Plant data collected with the strain gauge set in tension and held horizontal
Flume data obtained with strain gauge set in compression.
Strain Gauge Settings - HORIZONTAL IN TENSION
Gauge fact 1.10
5 lbs = 1060 micro-inches / inch

Plant Type Blue Elderberry (Sambucus canadensis)

Plant Height (in) -	21
Stem to First Branch (in	2
Stem Diameter (in) -	1
Number of Stems -	1
Number of branches -	3

Number of leaves -	175
Leaf Thickness (in) -	0.018
Leaf Width (in) -	2.5
Leaf Length (in) -	0.75
Avg. Branch Diameter (in) -	0.213
Height of effective leave area (in)	16
Width of effective leave area (in)	18

	micro-inches/inch Around Stem	Force	With String	Force
Average force required to pull the topmost part of stem horizontal -	90	0.425	NA	NA
Average force required to pull the center of stem 45 degrees -	300	1.415	NA	NA
****** Deflection From Vertical (in) -				
Average force required to pull the center of stem horizontal -	NA	NA	NA	NA

DRAG AND VELOCITY DATA

Run #	Deflection (deg - horiz	With Leaves Counter	With Leaves Time (sec)	With Leaves Strain		Without Leaves Counter	Without Leaves Time (sec)	Without Leaves Strain
1		43	30	57		45	30	24
2	40	60	30	104		56	30	36
3		70	30	158		71	30	45
4	20	88	30	300		78	30	55
5		99	30	370		98	30	87
6		107	30	435		119	30	117
7	20	122	30	510		130	30	152
8	0	140	30	590	40	146	30	217
9		153	30	710		184	30	304
10		NA	NA	NA		192	30	422

Additional Notes - The trunk would not bend . Only the branches bent, but the whole plant did not go into a teardrop shape. The overall structure stayed the same.

Analysis Blue Elderberry (Sambucus canadensis)

Run #	With Leaves Velocity (ft/sec)	With Leaves Drag Force (lbs)	Without Leaves Velocity (ft/sec)	Without Leaves Drag Force (lbs)
1	1.21	0.269	1.27	0.113
2	1.68	0.491	1.57	0.170
3	1.96	0.745	1.99	0.212
4	2.46	1.415	2.18	0.259
5	2.76	1.745	2.73	0.410
6	2.98	2.052	3.31	0.552
7	3.39	2.406	3.61	0.717
8	3.89	2.783	4.06	1.024
9	4.25	3.349	5.11	1.434
10	NA	NA	5.33	1.991

Drag force (lbs) at 2 ft/sec = 0.801

Plant Parameters Date - 10-20-94
Prop # - 84574 Run -

NOTE: Plant data collected with the strain gauge set in tension and held horizontal
Flume data obtained with strain gauge set in compression.
Strain Gauge Settings - HORIZONTAL IN TENSION
Gauge fact 1.10
5 lbs = 1040 micro-inches / inch

Plant Type French Pink Pussywillow (Salix caprea pendu		Number of leaves -	90
		Leaf Thickness (in) -	
Plant Height (in) -	36	Leaf Width (in) -	1.5
Stem to First Branch (i	3	Leaf Length (in) -	0.5
Stem Diameter (in) -	0.75	Avg. Branch Diameter (in) -	0.235
Number of Stems -	1	Height of effective leave area (in)	10
Number of branches -	4	Width of effective leave area (in) -	10

stem to leaves = 25"

	micro-inches/inch Around Stem	Force	With String	Force
Average force required to pull the topmost part of stem horizontal -	70	0.337	NA	NA
Average force required to pull the center of stem 45 degrees -	120	0.577	NA	NA
****** Deflection From Vertical (in) -				
Average force required to pull the center of stem horizontal -	260	1.250	NA	NA

DRAG AND VELOCITY DATA

Run #	Deflection (deg - hori	With Leaves Counter	With Leaves Time (sec)	With Leaves Strain	Without Leaves Counter	Without Leaves Time (sec)	Without Leaves Strain
1		48	30	40	50	30	40
2	40	71	30	130	55	30	60
3		81	30	140	83	30	78
4		92	30	172	86	30	94
5		102	30	230	90	30	110
6		120	30	280	104	30	174
7		130	30	380	120	30	210
8		NA	30	NA	NA	30	NA
9		NA	30	NA	NA	30	NA
10		NA	30	NA	NA	30	NA

Additional Notes - Branched tree. Branches left trunk immediately. Trunk did NOT bend only individual braches bent....entire plant did not go into teardrop shape

Analysis French Pink Pussywillow (Salix caprea pendula)

Run #	With Leaves Velocity (ft/sec)	With Leaves Drag Force (lbs)	Without Leaves Velocity (ft/sec)	Without Leaves Drag Force (lbs)
1	1.35	0.192	1.41	0.192
2	1.99	0.625	1.54	0.288
3	2.26	0.673	2.32	0.375
4	2.57	0.827	2.40	0.452
5	2.84	1.106	2.51	0.529
6	3.34	1.346	2.90	0.837
7	3.61	1.827	3.34	1.010
8	NA	NA	NA	NA
9	NA	NA	NA	NA
10	NA	NA	NA	NA

Drag force (lbs) at 2 ft/sec = 0.627

Plant Parameters		Date -	10-20-94
Prop # -	84574	Run -	

NOTE: Plant data collected with the strain gauge set in tension and held horizontal
Flume data obtained with strain gauge set in compression.
Strain Gauge Settings - HORIZONTAL IN TENSION

Gauge fact	1.10
5 lbs =	1040 micro-inches / inch

Plant Type Sycamore (Platenus acer ifolia)

Plant Height (in) -	36	Number of leaves -	23
Stem to First Branch (i	2	Leaf Thickness (in) -	
Stem Diameter (in) -	0.413	Leaf Width (in) -	6
Number of Stems -	1	Leaf Length (in) -	6
Number of branches -	3	Avg. Branch Diameter (in) -	0.025
		Height of effective leave area (in)	33
		Width of effective leave area (in) -	8

	micro-inches/inch Around Stem	Force	With String	Force
Average force required to pull the topmost part of stem horizontal -	148	0.712	NA	NA
Average force required to pull the center of stem 45 degrees -	274	1.317	NA	NA
****** Deflection From Vertical (in) -				
Average force required to pull the center of stem horizontal -	320	1.538	NA	NA

DRAG AND VELOCITY DATA

Run #	Deflection (deg - hori	With Leaves Counter	Time (sec)	Strain	Without Leaves Counter	Time (sec)	Strain
1	40	43	30	30	48	30	12
2	30	58	30	55	68	30	20
3	20	69	30	71	74	30	28
4	0	95	30	112	90	30	38
5		112	30	154	100	30	48
6		115	30	170	110	30	51
7		129	30	198	116	30	57
8		136	30	228	133	30	94
9		164	30	300	137	30	110
10		168	30	310	140	30	115

Additional Notes - Cut from shoot, one long branch & 2 small branches.

Analysis Sycamore (Platenus acer ifolia)

Run #	With Leaves Velocity (ft/sec)	Drag Force (lbs)	Without Leaves Velocity (ft/sec)	Drag Force (lbs)
1	1.21	0.144	1.35	0.058
2	1.63	0.264	1.90	0.096
3	1.93	0.341	2.07	0.135
4	2.65	0.538	2.51	0.183
5	3.12	0.740	2.79	0.231
6	3.20	0.817	3.06	0.245
7	3.59	0.952	3.23	0.274
8	3.78	1.096	3.70	0.452
9	4.55	1.442	3.81	0.529
10	4.66	1.490	3.89	0.553

Drag force (lbs) at 2 ft/sec = 0.360

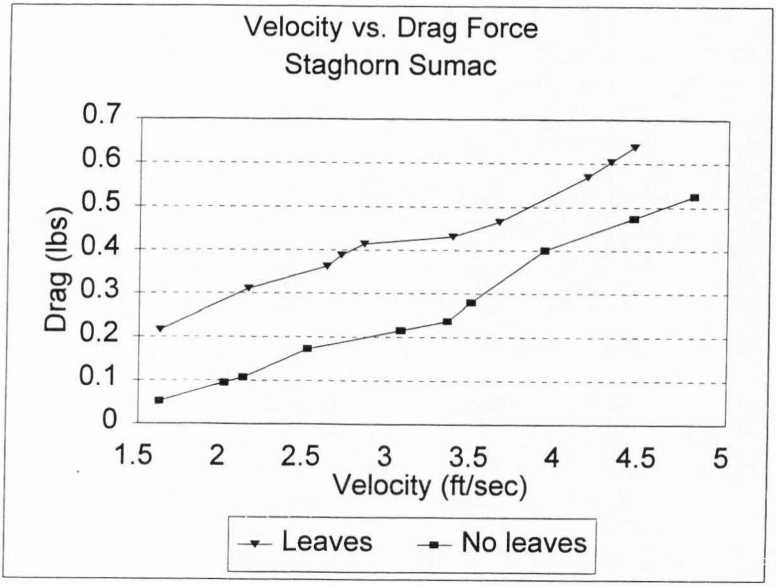

Figure A-1. Staghorn Sumac

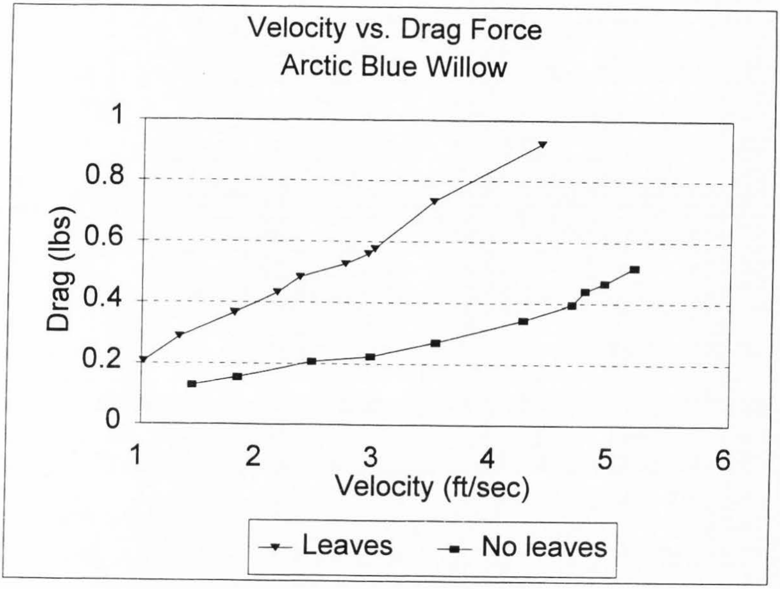

Figure A-2. Arctic Blue Willow

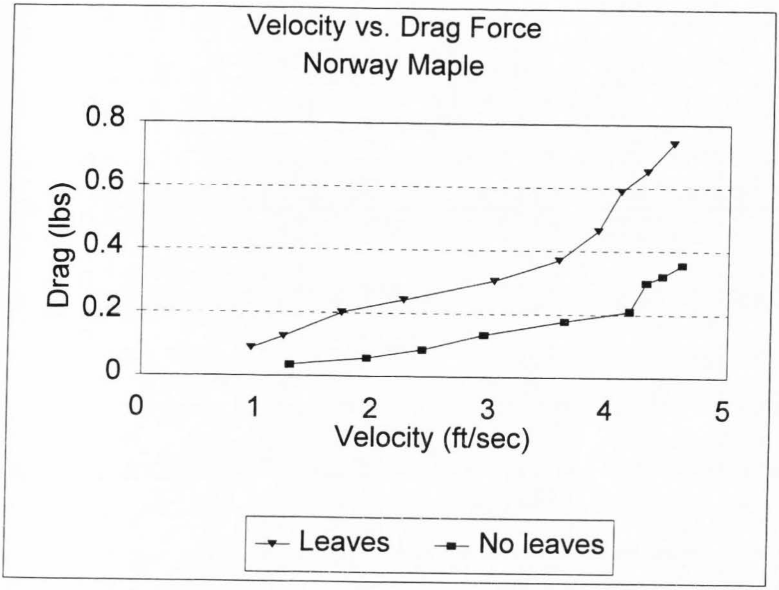

Figure A-3. Norway Maple

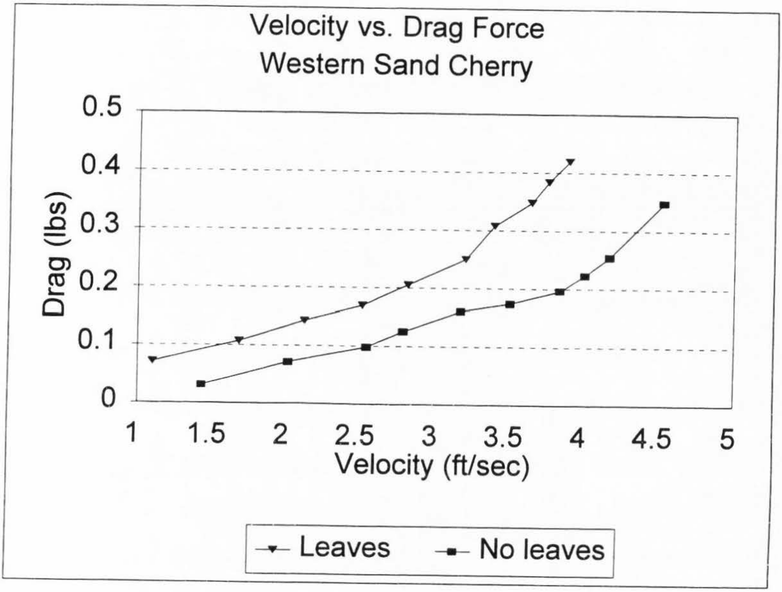

Figure A-4. Western Sand Cherry

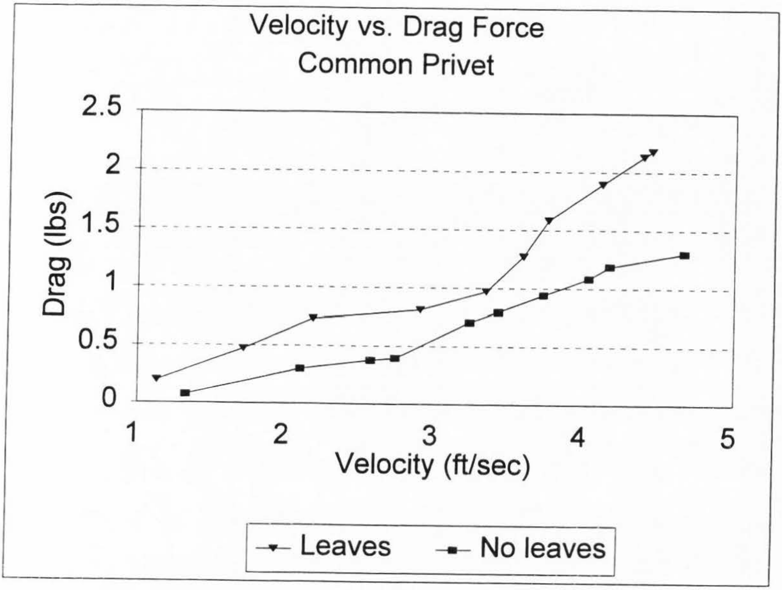

Figure A-5. Common Privet

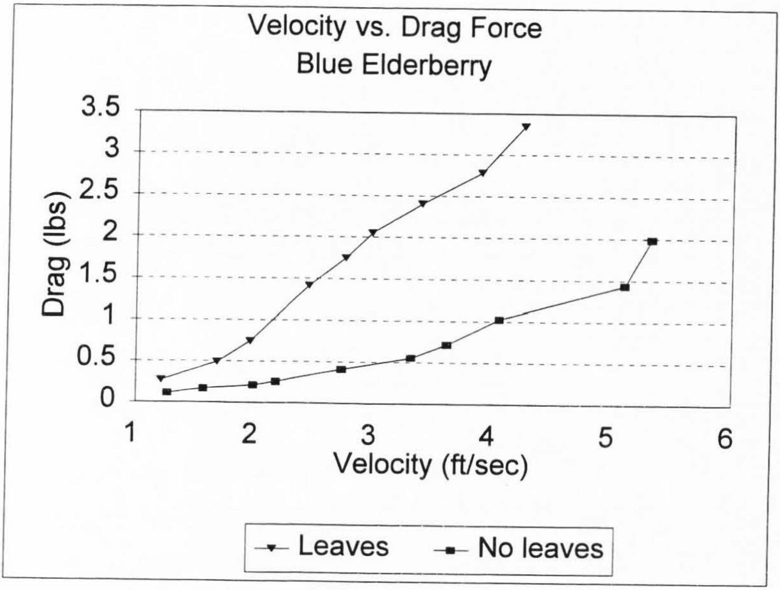

Figure A-6. Blue Elderberry

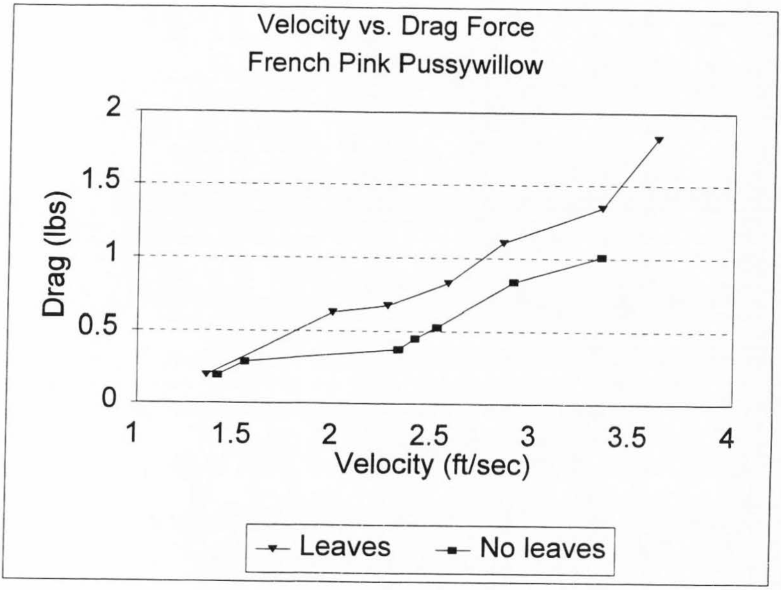

Figure A-7. French Pink Pussywillow

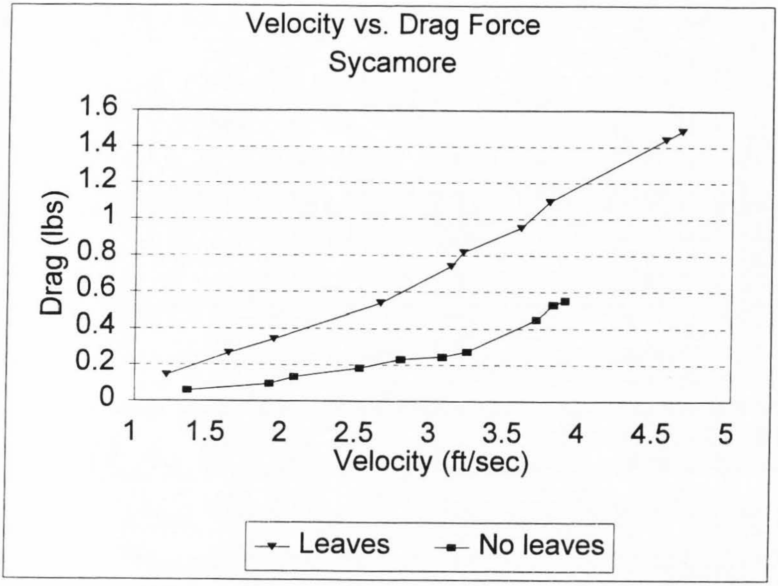

Figure A-8. Sycamore

Appendix B

Large Flume Data Sample and Examples

COE large flume statistical fit 2-7-96

STATS_4e.WK4
partially submerged

CONSTA	x1	x2	x3	R^2	Scatter
3.62E-09	-0.448097	-0.881535	1.060795	0.887835	0.377436

Cd= CONSTANT * [p V² A / E As]^x1 * [M A]^x2 * Re^x3

	Yo ft	Velocity V fps	Energy slope S	V*/V	Plant ht H ft	eff Plant widt W ft	Stem area tot As ft²	Plant dens M 1/ft^2
lg dogs	2.685	1.653	0.003222	0.315801	2.685	2.166667	0.010908	0.0494
salt cedar	3.66	2.35	0.0038	0.281112	3.66	2	0.008522	0.0575
	3.062	2.246	0.00369	0.264379	3.062	2	0.008522	0.0575
	2.768	2.462	0.00513	0.271671	2.768	2	0.008522	0.0575
	2.714	3.067	0.00517	0.214812	2.714	2	0.008522	0.0575
willows	2.232	2.257	0.00175	0.151984	2.232	1	0.003068	0.2125
	2.974	2.984	0.00333	0.18581	2.974	1	0.003068	0.2125
	2.693	2.59	0.00326	0.201843	2.693	1	0.003068	0.2125
	2.547	2.381	0.00228	0.177721	2.547	1	0.003068	0.2125
mtn willow	2.226	2.061	0.00323	0.231291	2.226	1.5	0.012272	0.45
	1.986	2.309	0.00414	0.219177	1.986	1.5	0.012272	0.45
	2.451	2.137	0.00666	0.336376	2.451	1.5	0.012272	0.45
	2.683	1.999	0.00616	0.363329	2.683	1.5	0.012272	0.45
	3.063	2	0.00584	0.377656	3.063	1.5	0.012272	0.45
	3.582	1.71	0.00459	0.421234	3.582	1.5	0.012272	0.45
	4.104	1.462	0.00306	0.432387	4.104	1.5	0.012272	0.45
	4.351	1.379	0.00274	0.446282	4.351	1.5	0.012272	0.45

	eff Plant ht H' ft	eff Plant area A" ft²	Plant Vp Fps	Plant Fd lbs	net H" ft	Flex E psf	Cd
lg dogs	2.5	5.416667	3.4	8.6	2.5	21264908	0.745415
salt cedar	4.5	9	NA	NA	4.5	27280663	0.305406
	4.5	9	NA	NA	4.5	27280663	0.27013
	4.5	9	NA	NA	4.5	27280663	0.285238
	4.5	9	NA	NA	4.5	27280663	0.178334
willows	4	4	NA	NA	4	4552087	0.054351
	4	4	NA	NA	4	4552087	0.081236
	4	4	NA	NA	4	4552087	0.09586
	4	4	NA	NA	4	4552087	0.074317
mtn willow	4	6	NA	NA	4	23300000	0.039626
	4	6	NA	NA	4	23300000	0.035584
	4	6	NA	NA	4	23300000	0.083814
	4	6	NA	NA	4	23300000	0.097784
	4	6	NA	NA	4	23300000	0.105647
	4	6	NA	NA	4	23300000	0.131436
	4	6	NA	NA	4	23300000	0.138488
	4	6	NA	NA	4	23300000	0.147532

VEGETATION RESISTANCE IN FLOOD PLAINS

enter the plant ty | example of small dogwood

enter the plant characteristics

plant height in inches	20	1.6667	feet
effective plant height in inches	13	1.0833	feet
effective plant width in inches	9	0.75	feet
stem diameter in inches	0.375	0.0313	feet
number of stems	1		
plant density in number per square fo	0.49827		
enter the resistance index in lbs/ft²	6.70E+06		

to calculate resistance index
enter force to bend plant
45 degrees | 0.3387

I (ft^4) = 4.7E-08
E (lbs/ft²) *********

enter flow characteristics

average flow velocity in fps	1.2
flow depth in feet	4.17
hydraulic raduis in feet	3.944

Yo/H =	2.502	PLANTS ARE FULLY SUBMERGED 1
A stems	0.000767	ft²
eff H =	1.083333	ft for submerged plants
A plant =	0.8125	ft²
Fi/Fb =	2264.004	
H/Y =	0.39968	
M A =	0.404844	
Reynolds	***********	

drag coefficient then equals	0.231	Cd	
resistance coefficient equals	0.216	V*/V	0.2995
Manning's resistance equals	0.071	n	

EXAMPLE: Find the resistance and depth of flow for a flood plain that is 80 feet wide and covered with a combination of salt cedars and willows. The flow acorss the flood plain is 1200 cfs. The slope of the plain was 0.03.
The density of water is 1.94 slug/ft3 and the dynamic viscosity is 1.25E-5 ft²/s.

In a sample plot of 20 feet by 20 feet, there were 40 willows and 20 salt cedars. The average dimensions of the willows were: a stem diameter of 1/2" with 5 stems per plant, an average plant height of 4 feet, a width of leaf mass of 3 feet, a height of leaf mass of 3 feet, and a force of 3 lbs necessary to bend a representative stem to 45 degrees.

The average dimensions of the salt cedars were: a stem diameter of 5/8" with 3 stems per plant, an average plant height of 6 feet, a width of leaf mass of 3 feet, a height of leaf mass of 4 feet, and a force of 5 lbs necessary to bend a representative stem to 45 degrees.

Willows:		Salt Cedars:	
H (ft) =	4	H (ft) =	6
W (ft) =	3	W (ft) =	3
H" (ft) =	3	H" (ft) =	5
Ds (ft) =	0.042	Ds (ft) =	0.052
# Stems	5	# Stems	3
calc As	0.007	calc As	0.006
calc A (f	9.000	calc A (f	15.000
Fb (lbs)	3.000	Fb (lbs)	5.000
calc I (ft	********	calc I (ft	********
calc E (I	********	calc E (I	********
Plants/4	40	Plants/4	20
calc M (	0.100	calc M (	0.050

calculate Average Plant:

Mtotal =	0.150		
Mi/Mtot	0.667		
Mi/Mtot	0.333		
H avg (f	22.098		
W avg (f	13.110		
H" avg (	17.728		
Ds avg	0.206	A =	53.184
As avg (	0.029	A* =	187.84
A avg (ft	53.184		
I avg (ft	********		
E avg (I	********		

assume that plants are submerged (Yo>4.67 ft)

		n	Q	Y
guess d	0.6			
width (ft	80	0.96	1500	16.2
flow (cfs	150	0.97	1200	14.3
slope =	0.03	0.98	1000	12.9
calc flo	48	0.99	800	11.3
calc V (f	3.125	1	********	9.6
calc Rh	0.6	1.01	400	7.6
calc V*	0.761	1.04	********	5.1
calc V*/	0.244		********	

calculate resistance:

[E As] /	0.0
[H/Yo} =	
[M A] =	447.25
[Re} =	********
therfor	0.000
n =	0.00
calc V*	0.000
calc Rh	0.0
Rh gues	0.6

Table B-1. Summary of Large Flume Test Results

Run	Plant density /ft²	Yo ft	avg V fps	n test	Fd lbs	Vp fps	Sf	f corr walls	f net	n net
Runs 0-1 to 0-3 were with a plain bed and no plants.										
0-2	0.000	4.334	0.687	0.016			0.0000	0.0148	0.0325	0.020
0-1	0.000	2.355	1.274	0.017			0.0001	0.0147	0.0381	0.020
0-3	0.000	4.788	1.940	0.016			0.0002	0.0122	0.0357	0.022
Runs 1-1 to 1-6 were with 20 each Service Berry in a 400 sf test bed.										
1-1	0.050	2.265	1.148	0.063	3.500	1.5	0.0014	0.0238	0.6244	0.084
1-5	0.050	3.786	1.684	0.050	7.745	1.3	0.0013	0.0191	0.4342	0.076
1-2	0.050	3.173	1.844	0.050	4.989	2.0	0.0018	0.0193	0.4148	0.072
1-3	0.050	2.634	2.249	0.043	8.564	2.8	0.0023	0.0181	0.2931	0.059
1-6	0.050	4.182	2.257	0.042	9.234	1.0	0.0016	0.0169	0.3122	0.065
1-4	0.050	3.062	2.964	0.038	14.298	3.4	0.0028	0.0162	0.2338	0.054
Runs 2-1 to 2-6 were with 20 Service Berry, 68 Dogwood, and 68 Euonymus										
2-1	0.390	4.638	1.159	0.062	7.000	0.6	0.0008	0.0215	0.7216	0.101
2-2	0.390	4.588	1.594	0.054	8.191	0.6	0.0012	0.0194	0.5417	0.087
2-5	0.390	3.096	1.837	0.059	7.819	1.6	0.0025	0.0205	0.5793	0.085
2-3	0.390	4.222	2.161	0.052	9.979	1.6	0.0022	0.0183	0.4880	0.082
2-4	0.390	2.979	2.434	0.055		2.2	0.0040	0.0191	0.4981	0.078
2-6	0.390	2.249	2.557	0.055	11.766	3.0	0.0055	0.0197	0.4745	0.073
Runs 3-1 to 3-4 were with no Service Berry, 68 Dogwood, and 68 Euonymus										
3-1	0.340	4.627	1.181	0.055		0.8	0.0007	0.0206	0.5631	0.089
3-4	0.340	3.222	1.552	0.050			0.0013	0.0198	0.4158	0.072
3-2	0.340	4.152	1.761	0.048			0.0013	0.0185	0.4105	0.075
3-3	0.340	2.388	2.094	0.050		2.1	0.0029	0.0196	0.3934	0.067
Runs 4-1 to 4-4 were with no Service Berry, 68 Dogwood, and no Euonymus										
4-1	0.170	4.455	0.477	0.095			0.0003	0.0293	1.6938	0.154
4-2	0.170	4.558	1.124	0.063			0.0008	0.0218	0.7409	0.102
4-3	0.170	4.136	1.994	0.040			0.0011	0.0170	0.2805	0.062
4-4	0.170	3.546	3.173	0.032			0.0020	0.0148	0.1685	0.046
Runs 5-1 to 5-4 were with no Service Berry, no Dogwood, and 68 Euonymus										
5-1	0.170	3.921	1.377	0.037			0.0005	0.0178	0.2342	0.056
5-3	0.170	1.610	2.679	0.038			0.0038	0.0181	0.2137	0.046
5-2	0.170	4.558	2.911	0.029			0.0012	0.0141	0.1464	0.045
5-4	0.170	2.320	3.158	0.036			0.0034	0.0162	0.1944	0.047

Table B-1. Continued

Run	Plant density /ft²	Yo ft	avg V fps	n test	Fd lbs	Vp fps	Sf	f corr walls	f net	n net
Runs 6-1 to 6-4 were with 22 each Mulefat in a 400 sf test bed.										
6-1	0.060	4.668	1.339	0.037	0.123	1.4	0.0175	0.2461	2.2998	0.059
6-2	0.060	4.151	2.108	0.035	0.223	2.3	0.0161	0.2118	1.8987	0.053
6-3	0.060	4.474	2.375	0.033	NA	NA	0.0153	0.1916	1.9539	0.051
6-4	0.060	3.518	2.594	0.030	NA	NA	0.0150	0.1461	1.2627	0.043
Runs 7-1 to 7-4 were with 22 Mulefat and 70 Alders in a 400 sf test bed.										
7-1	0.230	4.370	1.201	0.066	0.040	NA	0.0220	0.8034	3.0870	0.106
7-2	0.230	4.411	1.496	0.052	NA	NA	0.0195	0.4939	2.7834	0.083
7-3	0.230	3.766	2.048	0.047	NA	NA	0.0181	0.3820	2.1870	0.071
7-4	0.230	3.301	2.772	0.050	NA	NA	0.0178	0.4198	1.9646	0.073
Runs 8-1 to 8-6 were with 22 Mulefat and 70 Alders and 64 Valley Elderberry in a 400 sf test bed.										
8-1	0.390	4.506	1.451	0.073	0.638	0.65	0.0220	0.9989	3.3209	0.119
8-2	0.390	4.397	1.714	0.070	1.277	1.1	0.0211	0.9097	3.1873	0.113
8-3	0.390	4.517	2.380	0.065	1.638	1.7	0.0193	0.7905	3.1953	0.106
8-4	0.390	3.901	1.750	0.075	1.404	1.35	0.0218	1.0062	2.8675	0.116
8-5	0.390	3.650	1.860	0.075	NA	NA	0.0218	0.9864	2.6682	0.114
8-6	0.390	3.826	1.750	0.065	1.511	1.5	0.0208	0.7471	2.6553	0.100
Runs 9-1 to 9-4 were with no Mulefat and no Alders and 64 Valley Elderberry in a 400 sf test bed.										
9-1	0.160	4.482	0.926	0.083	NA	NA	0.0249	1.2928	3.4356	0.135
9-2	0.160	4.365	1.400	0.070	NA	NA	0.0219	0.9065	3.1581	0.113
9-3	0.160	3.515	1.714	0.068	NA	NA	0.0214	0.7992	2.4645	0.102
9-4	0.160	2.999	2.038	0.072	NA	NA	0.0217	0.8632	2.1227	0.103

Table B-1. Continued

Run	Plant density /ft²	Yo ft	avg V fps	n test	Fd lbs	Vp fps	Sf	f corr walls	f net	n net
Runs 10-1 to 10-3 were with 23 each (SUBMERGED) Salt Cedar in a 400 sf test bed.										
10-1	0.058	4.692	1.364	0.072	NA	NA	0.0016	0.0220	0.9855	0.119
10-2	0.058	4.522	1.902	0.063	NA	NA	0.0024	0.0199	0.7410	0.102
10-3	0.058	3.660	2.350	0.060	NA	NA	0.0038	0.0193	0.6269	0.091
Runs 10-4 to 10-6 were with 23 each (PARTIALLY SUBMERGED) Salt Cedar in a 400 sf test bed.										
10-4	0.058	3.062	2.246	0.058	NA	NA	0.0037	0.0197	0.5585	0.083
10-5	0.058	2.768	2.462	0.060	NA	NA	0.0051	0.0199	0.5860	0.084
10-6	0.058	2.714	3.067	0.048	NA	NA	0.0052	0.0177	0.3703	0.066
Runs 11-1 to 11-3 were with (SUBMERGED) 23 each Salt Cedar; 83 tall willows; and 50 short willows in a 400 sf test bed.										
11-1	0.390	4.702	2.159	0.062	0.765957	1.85	0.0029	0.0193	0.7278	0.102
11-2	0.390	4.330	2.604	0.062	NA	0	0.0044	0.0188	0.7074	0.099
11-3	0.390	4.716	1.317	0.075	0.053191	0.25	0.0016	0.0225	1.0730	0.124
Runs 11-4 to 11-7 were with (PARTIALLY SUBMERGED) 23 each Salt Cedar; 83 tall willows; and 50 short willows in a 400										
11-4	0.390	3.133	1.731	0.070	NA	NA	0.0031	0.0219	0.8231	0.102
11-5	0.390	2.583	2.120	0.065	NA	NA	0.0047	0.0212	0.6805	0.089
11-6	0.390	2.669	3.147	0.059	NA	NA	0.0083	0.0190	0.5630	0.082
11-7	0.390	2.182	2.383	0.053	NA	NA	0.0046	0.0198	0.4382	0.070
Runs 12-1 to 12-3 were with (SUBMERGED) 83 tall willows; and 50 short willows in a 400 sf test bed.										
12-1	0.333	4.646	1.162	0.060	NA	NA	0.0008	0.0213	0.6749	0.098
12-2	0.333	4.677	1.809	0.046	NA	NA	0.0011	0.0179	0.3913	0.074
12-3	0.333	4.554	2.503	0.045	NA	NA	0.0021	0.0168	0.3714	0.072
Runs 12-4 to 12-7 were with (PARTIALLY SUBMERGED) 83 tall willows; and 50 short willows in a 400 sf test bed.										
12-4	0.333	2.974	2.984	0.041	NA	NA	0.0033	0.0167	0.2722	0.058
12-5	0.333	2.693	2.590	0.045	NA	NA	0.0033	0.0179	0.3234	0.062
12-6	0.333	2.547	2.381	0.040	NA	NA	0.0023	0.0175	0.2510	0.054
12-7	0.333	2.232	2.257	0.035	NA	NA	0.0017	0.0172	0.1868	0.045

Table B-1. Continued

Run	Plant density /ft²	Yo ft	avg V fps	n test	Fd lbs	Vp fps	Sf	f corr walls	f net	n net
Runs 13-1 to 13-8 were with 36 mountain willows (5 stems each) (partially SUBMERGED) in a 400 sf test bed.										
13-1	0.450	2.226	2.061	0.052	NA	NA	0.0032	0.4222	2.1681	0.069
13-2	0.450	1.986	2.309	0.050	NA	NA	0.0041	0.3852	1.9370	0.064
13-3	0.450	2.451	2.137	0.075	NA	NA	0.0067	0.9018	2.4140	0.102
13-4	0.450	2.683	1.999	0.080	NA	NA	0.0062	1.0441	2.6439	0.112
13-5	0.450	3.063	2.000	0.082	NA	NA	0.0058	1.1291	3.0161	0.119
13-6	0.450	3.582	1.710	0.090	NA	NA	0.0046	1.4198	3.5295	0.136
13-7	0.450	4.104	1.462	0.090	NA	NA	0.0031	1.4804	4.0372	0.143
13-8	0.450	4.351	1.379	0.092	NA	NA	0.0027	1.5790	4.2801	0.149
Runs 13-8 to 13-11 were with 36 mountain willows (5 stems each) (SUBMERGED) in a 400 sf test bed.										
13-8	0.450	4.351	1.465	0.088	NA	NA	0.0028	1.4431	4.2755	0.142
13-9	0.450	4.639	1.725	0.083	NA	NA	0.0033	1.3122	4.5494	0.137
13-10	0.450	4.194	1.967	0.080	NA	NA	0.0043	1.1752	4.1139	0.127
13-11	0.450	4.534	2.936	0.062	NA	NA	0.0055	0.7193	4.4062	0.101
Run 14-1 was with 36 mountain willows (5 stems each) (PARTIALLY SUBMERGED) NO LEAVES										
14-1	0.450	2.869	1.952	0.066	NA	NA	0.0038	0.7162	2.8090	0.093
Run 14-2 was with36 mountain willows (5 stems each) (SUBMERGED) in a 400 sf test bed. NO LEAVES										
14-2	0.450	4.515	1.207	0.075	NA	NA	0.0014	1.0555	4.4073	0.122

Appendix C

Summary of Regression Analysis Results

Submerged flow

$$\frac{V^{*}}{V} = 0.326 \left(\frac{E\,A_s}{\rho\,V^2 A} \right)^{0.128} \left(\frac{H}{Y_O} \right)^{0.187} (M\,A)^{0.182} \left(\frac{1}{R_E} \right)^{0.0828}$$

r^2 *by corrected sum of squares* = 0.956

maximum scatter of data = 15%

maximum scatter of data for multiple plant types = 20%

$$\frac{V^{*}}{V} = 0.190 \left(\frac{\frac{2\,F_{45}}{H} D_s}{\rho\,V^2 A} \right)^{0.104} \left(\frac{H}{Y_O} \right)^{0.278} (M\,A)^{0.126} \left(\frac{1}{R_E} \right)^{0.0976}$$

r^2 *by corrected sum of squares* = 0.805

maximum scatter of data = 32%

$$\frac{V^{*}}{V} = 1.153 \left(\frac{F_{45}}{\rho\,V^2 A} \right)^{0.122} \left(\frac{H}{Y_O} \right)^{0.256} (M\,A)^{0.144} \left(\frac{1}{R_E} \right)^{0.0814}$$

r^2 *by corrected sum of squares* = 0..862

maximum scatter of data = 28%

$$\frac{V^{*}}{V} = 0.354 \left(\frac{M\,E\,A_s}{\gamma\,Y_O\,S} \right)^{0.164} \left(\frac{H}{Y_O} \right)^{0.246} (M\,A)^{0.076} \left(\frac{1}{R_E} \right)^{0.1398}$$

r^2 *by corrected sum of squares* = 0.919

maximum scatter of data = 20%

maximum scatter of data for multiple plant types = 63%

$$\frac{V^{\bullet}}{V} = 5.231 \left(\frac{M \dfrac{2F_{45}}{H} A_s}{\gamma S} \right)^{0.100} \left(\frac{H}{Y_O} \right)^{0.259} (MA)^{0.0314} \left(\frac{1}{R_E} \right)^{0.185}$$

r^2 *by corrected sum of squares* = 0.832

maximum scatter of data = 29%

Partially submerged flow

$$\frac{V^{\bullet}}{V} = 4.5x10^{-5} \left(\frac{E A_S}{\rho V^2 A*} \right)^{0.224} (MA*)^{0.0592} \left(R_E \right)^{0.530}$$

r^2 *by corrected sum of squares* = 0.834

maximum scatter of data = 19%

$$\frac{V^{\bullet}}{V} = 3.28x10^{-2} (MA*)^{0..204} \left(R_E \right)^{0.158}$$

r^2 *by corrected sum of squares* = 0.271

maximum scatter of data = 52%

$$\frac{V^{\bullet}}{V} = 1.27x10^{-6} \left(\frac{M E A_S}{\gamma Y_O S} \right)^{0.279} (MA*)^{0.145} \left(R_E \right)^{0.708}$$

r^2 *by corrected sum of squares* = 0.494

maximum scatter of data = 36%

VITA

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Doctor of Philosophy

Dissertation: Predicting Resistance and Stability of Vegetation in Floodplains

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