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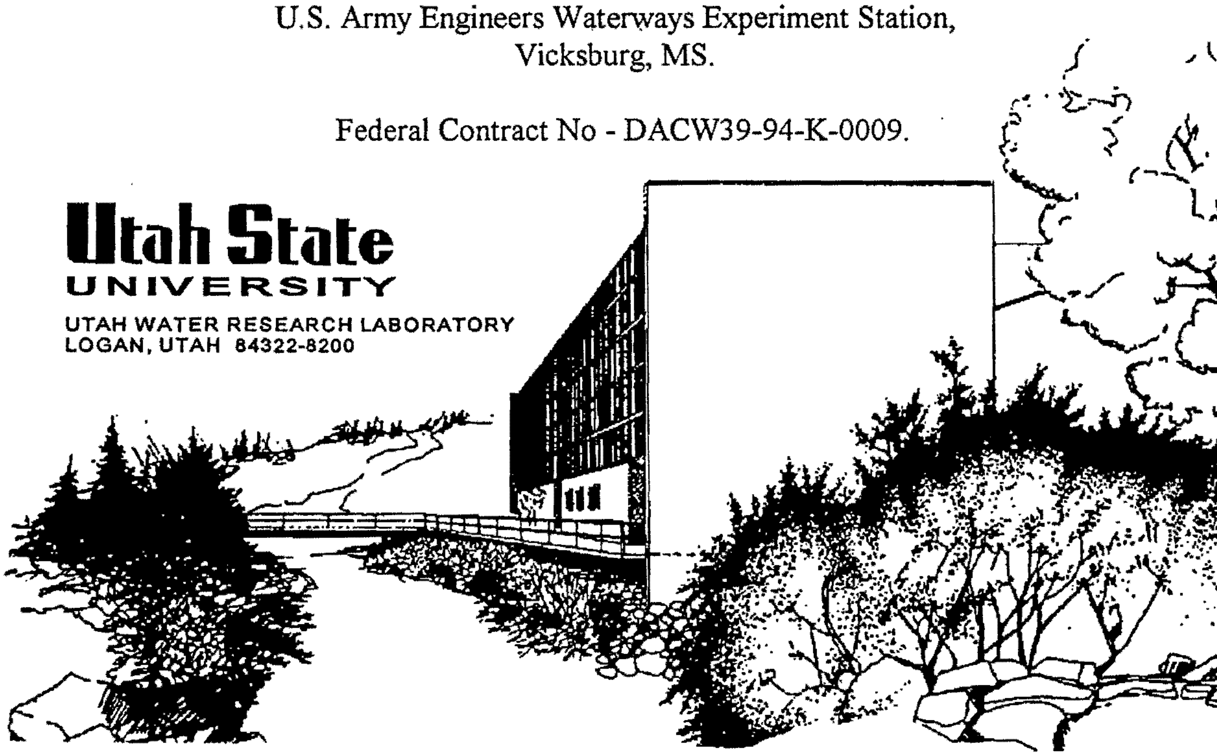

THE STUDY OF THE RESISTANCE AND STABILITY OF VEGETATION ECOSYSTEM PLANT GROUPINGS IN FLOOD CONTROL CHANNELS: VOL. 1

PREFACE

The following report was prepared by the Utah Water Research Laboratory of Utah State University in Logan, Utah. Volume 1 of the UWRL report USU-400A contains the data summary and conclusions of flow tests conducted with different plant types and ecosystem groupings of shrubs and woody vegetation in the hydraulics flumes of Utah State University. The methodology and equations that were developed to predict flow resistance for multiple plant types include the effects of plant flexibility, varying plant density, plant characteristics, and multiple plant stems. The study included over 214 flow tests, testing of 20 different plant types, 5 different combinations or groupings of plants, and the measurements of flow resistance, plant drag forces, velocity profiles, and shear stress. The analysis and development included a comparison with the methods of other researchers and a comparison with field data collected from several river systems. A detail example is presented to demonstrate an iterative solution for determining flow depth and resistance of a flood plain with several types of plant cover. Volume 2 of the UWRL report USU-400B contains the test data from the two phases of large flume testing (Appendix A and B), the test data from the sectional flume testing (Appendix D), and a discussion of Compound Flood Channels (Appendix E).

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 study was conducted under the supervision of Dr. William Rahmeyer of Utah State University, and was aided by Dave Werth of Utah State University. The project was coordinated with Dave Derrick and Gary Freeman of the U.S. Army Engineers Waterways Experiment Station. Appreciation is also expressed to Ron Copeland, Brad Hall, and Craig Fischenich of the U.S. Army Engineers Waterways Experiment Station for their review of the project results.

NOMENCLATURE

The following symbols and units were used in this report:

a	Coefficient used by Kouwen and Li, dimensionless.
A	Frontal area of an individual plant blocking flow, ft^2.
A*	Net area of a partially submerged plant blocking flow, ft^2.
A_S	Total cross sectional area of the stems of an individual plant, ft^2.
b	Coefficient used by Kouwen and Li, dimensionless.
b	Bed width, ft.
C	Chezy resistance coefficient, $ft^{1/2}$/sec.
C_D	Drag coefficient of vegetation, dimensionless.
dy/dx	Unit change in slope of water surface, dimensionless.
D_S	Stem diameter, ft.
d_{84}	Bed material size that equals or exceeds 84% of particles sizes, ft.
E	Modulus of elasticity of the vegetation, psf or Pascal.
f	Friction factor, dimensionless.
F_B	Total force on channel bottom produced by vegetation, lbs.
Fr	Froude number, dimensionless.
F_{45}	The horizontal force necessary to bend a plant stem 45 degrees, lbs.
g	Gravitational constant = 32.2 ft/s^2.
H	Undeflected plant height, ft.
H'	Undeflected height of the leaf mass of a plant, ft.
H*	Effective submerged height of the leaf mass, ft.
I	Second moment of inertia of cross section of plant stem, ft^4 or m^4.
k	Deflected roughness height, ft.
L	Length of channel reach, ft.
M	Relative plant density, number of plants per ft^2.
M'	Plant density ratio, number of plants per m^2 / 1 plant per m^2.
m	Correction factor for channel meandering, dimensionless.
n	Manning's resistance coefficient, dimensionless.
n_b	Manning's resistance coefficient for bed roughness and vegetation, dimensionless.
n_{base}	Manning's resistance coefficient for bed roughness, dimensionless.
n_0	Manning's resistance coefficient for base roughness, dimensionless.
n_{veg}	Manning's resistance coefficient for vegetation, dimensionless.
P	Wetted perimeter of channel, ft.
Q	Flow rate or discharge, cfs.
R_h	Hydraulic radius (R=A/P), ft.
R	Gross hydraulic radius, ft.
R_b	Hydraulic radius due to resistance of bed and vegetation, ft.
R_w	Hydraulic radius due to resistance of flume walls, ft.
$\mathbf{R_E}$	Reynold's number, dimensionless.

S	Bed or energy slope, dimensionless.
S_f	Energy grade line slope, dimensionless.
S_o	Bed slope, dimensionless.
TL_A	Total leaf area, ft^2.
V	Mean channel velocity, fps.
V_{crit}	Critical velocity used by Kouwen and Li, fps.
V_P	Plant approach velocity at center of plant, fps.
V^*	Shear velocity ($V^*=[gRS]^{1/2}$), fps.
V^*/V	Resistance coefficient, dimensionless
Y_O	Flow depth, ft.
y_n	Normal flow depth, ft.
W	Plant width, ft.
γ	Specific weight of water, lbs/ft^3.
ν	Fluid dynamic viscosity, ft^2/s.
ρ	Fluid density, $Slugs/ft^3$.
τ_o	Shear stress on channel bottom ($\tau_o=\gamma RS$), lbs/ft^2

CONVERSION FACTORS

The following report is written exclusively in the EI (English) systems of units. The units can be converted to the SI(Metric) systems with the following conversions:

1 foot = 0.3048 meters
1 square foot = .092903 $meters^2$
1 cubic foot = 0.028317 $meters^3$
1 pound force = 4.44822 Newtons
1 psf = 47.88026 Pascal

The following conversions can be used to convert the Manning's resistance coefficient n, note that units are based on the English system:

$$n = (8g)^{1/2} \cdot 1.486 \cdot R^{1/6} / C$$
$$n = f^{2} \cdot 1.486 \cdot R^{1/6}$$
$$n = (8)^{1/2} \cdot 1.486 \cdot R^{1/6} \cdot V^*/V$$

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section 1 INTRODUCTION

1-1 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 flood plain as well as along the banks can increase and or even decrease the effective flow resistance (V*/V) or Manning's coefficient (n) during overbank flooding. The vegetation may be in place due to aesthetic reasons, natural conditions, or planned measures for erosion control. The following is a study of the flow resistance testing of plant ecosystem groupings. A plant ecosystem grouping is the combination of two to three different sizes or types of plants typically found in a specific geographical region.

1-2 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 flood plains and over-bank flooding, the effects of emergent vegetation on the flood plains must be considered. Over-bank flow onto the flood plains typically submerges many types of shrubs and woody vegetation.

1-3 Research has been conducted on vegetation such as dense layered grasses and on the rigid blockage of cylindrical tree trunks. Very little has been studied on the resistance effects of shrubs and woody vegetation that are submerged or partially submerged by turbulent flows. The flexible stems and varying shapes of the plant's leaf mass, greatly complicate the understanding of resistance. Resistance of flexible stems and plant shapes can not be adequately explained with either a boundary roughness or a form drag approach.

1-4 The purpose of this study was to investigate the effect of woody vegetation, particularly ecosystem groupings of ground cover plants and shrubs, on flow resistance. Phase I of testing, completed in 1994, studied multiple plants of the same size and type for flow resistance. The main objective of the Phase II testing was to determine the resistance coefficients of vegetated flood channels with combinations or ecosystem groupings of different sizes and types of plants. The first goal of the study was to determine the head loss and resistance coefficients from the laboratory testing of plants in conditions as close to in situ as possible. The second goal was to develop the methodology and equations necessary to predict resistance for different types, sizes, and combinations of plants. The following investigation required the testing of numerous plants and plant densities in both a large laboratory flume and in a smaller sectional flume.

1-5 The study also included a number of secondary objectives:

1) The effects of flow velocity and depth on the resistance coefficient V*/V and on Manning's resistance coefficient *n*;
2) The effects of the geometry and characteristics of plants on the drag forces produced by the plants;
3) The relationship of drag force with the bed shear stress and the flow resistance of the channel;
4) The effect of groupings of different sizes and types of plants on flow resistance;
5) The effect of plants with multiple stems;
6) The effect of submerged and partially submerged flow conditions;
7) The effect of plants in a dormant stage without leaves.
8) Observations of plant distortion and bending during submerged flow conditions;
9) Observations of sediment transport and of the scour of bed material during testing;

1-6 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 resistance 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 2 FLOW RESISTANCE

2-1 The resistance to flow in waterways can be characterized by a roughness or resistance coefficient. One of the most commonly used equations for flow resistance is the Manning's equation (Equation 1), where the Manning's coefficient or Manning's *n* represents the resistance. The ratio of shear velocity (Equation 2) to mean velocity, V*/V, is another form of resistance coefficient. It has been used in theoretical developments by Prandtl and Einstein, and is very popular for predicting resistance due to bed forms in alluvial channels. The shear velocity ratio (Equation 3) is a form of the ratio of shear stress to inertial force. The ratio of shear velocity to mean velocity will be used in this report for the development of methodology to predict resistance. This report will also focus on Manning's coefficient since most methodologies and applications such as HEC-2 use Manning's *n* exclusively.

$$V = \frac{1.486}{n} R_h^{2/3} S^{1/2} \tag{1}$$

Where, V is the mean velocity of flow in feet per second; R_h is hydraulic radius, in feet; S is slope of the energy grade line, in feet per feet; *n* is Manning's resistance coefficient; and 1.486 is a unit conversion for English units, in $ft^{1/3}/sec$.

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

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

Other resistance equations do use different resistance coefficients such as the Darcy friction factor *f* (Equation 6) or the Chezy *C* (Equation 7). However, the conversions from Manning's *n* are straight forward and the following equations can easily be converted to either *C* or *f*.

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

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

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

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

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

2-2 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 (1959) 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 (1959) was also one of the first to publish that Manning' n could vary with the flow variables of depth and discharge.

2-3 Cowan (1956) formulated the first additive or linearization of n (Equation 8) that was basically the summarization of the effects of the primary flow geometries.

$$n = \left(n_o + n_1 + n_2 + n_3 + n_4\right)\cdot m_5 \tag{8}$$

Where, n_o 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 base roughness that includes the effect of vegetation as well as the base roughness.

2-4 Detailed tables of base and additive values can be found in publications by Chow (1959), Benson and Dalrymple (1967), Barnes (1967), and others. The derivation of Cowan's additive equation (Equation 2) 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 to uniform channels or uniform sub-sections, and prevents the use of the equation to determine an average channel resistance coefficient for situations such as over-bank flooding.

2-5 Limerinos(1970) 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 9.

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

Where d_{84} is the bed material size that equals or exceeds 84% of the particle sizes. The limitations of Equation 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' equation does not account for the effects of vegetation.

2-6 Jarrett (1984, 1985) 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 10.

$$n_0 = 0.39 \cdot S^{0.38} \cdot R^{-0.16} \tag{10}$$

Jarrett's analysis had an average standard error of 28% for Equation 10, and the equation is limited to stream slopes from .002 to as high as .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 data in the development of Equation 10, and therefor an additive method similar to the methods presented by Cowan (1956) or Arcement and Schneider (1989), would be needed along with Equation 10 to determine the overall roughness when vegetation is present.

2-7 Abdelsalam et al. (1992) analyzed 4 wide, vegetated canals in Egypt. They modified Manning's equation to provide Equation 11 which then accounted for resistance in wide canals with submerged, grassy, vegetation.

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

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.

2-8 Recent studies on flow resistance with grasses include the research by Kouwen and Li (1980). They adapted (Equation 12) the work by Keulegan (1938) 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 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.

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

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

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 (1980) have proposed a method utilizing Equation 14 as a means of determining k based on physical parameters of the vegetation.

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

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 un-deflected vegetation height; and γ = the weight density 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 1.

Table 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 15.

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

2-9 Since the method by Kouwen and Li applies to densely packed grasses, it cannot be directly applied to flood plains where vegetation includes other types of vegetation. It has to be assumed that the above method predicts a base value of resistance, $n_o = n_b$, 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 14 also does not account for the separate effects of velocity and flow depth on any distortion or change in shape of a plant.

2-10 Research by Thompson and Roberson (1976) 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 flow blockage of 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 resistance.

2-11 Ree and Crow (1977) 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 flow resistance of plants would decrease with increased velocity due to the bending of the plants. Frentyl (1962) also studied a crop type of plant, alfalfa, for shallow flows and noted the decrease of resistance with increased velocity. He attempted to relate resistance to flow parameters and ratios of plant characteristics.

2-12 One of the most recent works on blockage and drag forces was published by Kadlec (1990). 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 resistance 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.

2-13 Usually the larger vegetation such as shrubs and trees are found in the flood plains adjacent to the main channel. This type of vegetation is a major influence on flow depth and resistance during situations such as over-bank flooding. Since the larger types of vegetation constitute much of the resistance within flood plains, Petryk and Bosmajian (1975) proposed a method to calculate flow resistance based on the drag forces created by the larger plants. They derived Equation 16 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.

$$n = n_b \cdot \sqrt{1 + \left(\frac{C_d\ \Sigma A_i}{2gAL}\right) \cdot \left(\frac{1.486}{n_b}\right)^2 \cdot \left(\frac{A}{P}\right)^{4/3}} \qquad \textbf{(16)}$$

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 = the cross-sectional area of the flow, in square feet, ΣA_i = the total frontal area of vegetation blocking the flow in the reach, in square feet, L = the length of the channel reach being considered, in feet, and g = the gravitational constant, in feet per square second.

2-14 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 8), except that the additive resistance n_4 for other types of vegetation is excluded.

2-15 There are several limitations to using Petryk and Bosmajian's Equation 16. The channel velocity must be small enough to prevent bending or distortion of the shape of the vegetation, and large variations in velocity can not occur across the channel. Vegetation such as grasses and shrubs are 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 (Petryk, 1989). In channels during flooding, the velocities over the flood plains can be relatively high and large degrees of bending and distortion of vegetation will occur. Vegetation can also vary widely across a flood plain, and depths often submerge vegetation. However, when tree trunks dominate sections of a flood plain, this method can be used for predicting the total resistance coefficient.

2-16 Arcement and Schneider (1989) further developed Petryk's method by stating that the portion of the vegetation which cannot be measured directly or calculated as rigid flow blockage, should be included in Cowan's formula as n_V (Equation 17).

$$n_b = n_o + n_1 + n_2 + n_3 + n_V \tag{17}$$

Where, n_V accounts for vegetation, such as shrubs and grass, on the flood plain that cannot be measured directly or calculated as a flow blockage. Equation 16, as defined by Petryk, accounts only for rigid and measurable vegetation such as tree trunks.

2-17 It should then be possible to use Equations 16 and 17 to include the effects of trees, grasses, and shrubs in calculating the total resistance of a vegetated channel. The total base resistance n_b of Equation 17 can be determined from either a base n_o or a grass base resistance (Equation 14). The total resistance n is calculated from correcting the total base resistance n_b for the effects of trees by Equation 16. The additive resistance coefficient n_V in Equation 17 is due to the effects of vegetation such as shrubs and woody vegetation. The main purpose of this study is to develop a data base and methodology to determine n_V.

section 3 FLOW IN COMPOUND FLOOD CHANNELS

3-1 Cowan's additive equation (Equations 8) and the equations to predict resistance from vegetation (Equations 14, 15, 16, 17) are all based on the assumption of constant velocity, energy slope, and flow depth across the channel. Many flood channels such as those with over-bank 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.

3-2 Chow (1959) and Cowan (1956) have shown that there are many factors which 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 flood plains and over-bank flooding. Main flow channels which 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.

3-3 The flow conveyance method is a more mathematically rigorous method for compound channels, and has been assumed by most researchers to be the most fundamentally correct and accurate. Masterman and Thorne (1992) 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 flood plains. 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.

3-4 With the assumption of constant energy slope, the discharge of each section can be solved for iteratively, 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.

3-5 The <u>equivalent resistance method</u> 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. Chow (1959) presented three equations for determining an equivalent resistance. The development of these equations are based on applying a weighting factor to each section of the compound channel and then combining them appropriately.

3-6 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.

3-7 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:

$$n = \left(\frac{\Sigma \left(P_N \cdot n_N^{1.5} \right)}{\Sigma P_N} \right)^{2/3} \qquad \textbf{(18)}$$

3-8 Dracos and Hardegger (1987) 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.

3-9 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.

$$n = \left(\frac{\Sigma \left(P_N \cdot n_N^{2} \right)}{\Sigma P_N} \right)^{1/2} \qquad \textbf{(19)}$$

3-10 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 (Lotter, 1933).

$$n = \frac{\left(\Sigma P_N \cdot \Sigma R_N^{5/3}\right)}{\Sigma\left(\dfrac{P_N \cdot R_N^{5/3}}{n_N}\right)} \tag{20}$$

Where $R_1, R_2, \ldots, R_N$ are the hydraulic radii of each section. Equation 20 is actually a flow conveyance equation since the velocity does not have to be constant throughout the cross section.

3-11 The flow conveyance method and Equation 20 will yield the same results for a compound flood channel. The equivalent resistance method and Equations 10 and 11 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 flood plains. The difference in results between the two methods will, in part, depend on the magnitude of the resistance of the vegetation.

3-12 Both the flow conveyance method and Equation 20 utilize an iterative solution to solve for the flow depth or total discharge. The advantage of Equations 18 and 11 of the equivalent resistance method is 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 and iterative. 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 sub-section of the compound flood channel and used with either the flow conveyance or equivalent flow resistance methods.

3-13 A recent publication by Masterman and Thorne (1992) presents the application of Kouwen and Li's (1980) method for grasses with calculations in a compound channel. In their paper, they note that a rational method for emergent, nonflexible vegetation is being developed. Additional information on flow resistance and compound flood channels can be found in very comprehensive literature review by Craig Fischenich (1994).

section 4 SEDIMENT TRANSPORT WITH VEGETATION

4-1 It is common knowledge that the presence of vegetation in a channel or flood plain will effect 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 (ASCE 1960), and prevent or stabilize bed forms.

4-2 Another common belief is that the presence of vegetation increases flow resistance and then results in the reduction of flow velocity from 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 (1973) 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.

4-3 The limitations of Li and Shen's (1976) study include 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, 2 dimensional flow field around multiple cylinders. Tests of actual vegetation was not available for their study, and the 2 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 (Richardson, Simons, et al 1975) is a classical example of this type of phenomena. 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.

section 5 TEST FACILITY

5-1 The Utah Water Research Laboratory is a facility of Utah State University and is the water research center for the state of Utah. The laboratory was built in the late 1960's and has been involved both nationally and internationally in all areas of water engineering. The laboratory serves both the Environmental Engineering Division and the Water Division of the department of Civil Engineering at Utah State University. Over 20 professional faculty and engineers and approximately 60 graduate students are assigned to the Water Division at the laboratory. Part of the Utah Water Research Laboratory is the hydraulic's laboratory. The hydraulic's lab is one of the largest laboratories (outside of WEST) that is available for physical modeling and testing. Over 50,000 square feet of lab space and flows in excess of 150 cfs are available for the different models and flumes in the lab. The lab includes calibration facilities for NBS traceable calibrations of flow meters and velocity meters. Permanent support staff are available for construction and fabrication of the models.

5-2 Two flumes were used for the plant tests of this study. The large flume of the hydraulic's laboratory was used for multiple plant tests. The large flume is a 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 6 TEST PLANTS AND DIMENSIONS

6-1 There were thirteen different groups of plants tested in the large laboratory flume and ten 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 length of the test section. The spacing selected for the plants was based on the typical spacing (Kadlec 1990) of 1½ to 2 plant diameters for emergent plants The plants tested in the sectional flume were placed in a single row of 4 to 5 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 4 plants located upstream.

6-2 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 section flume and the drag force plant of the larger flume, were cantilevered into test platform and load cell. The roots of the cantilevered plants had to be removed.

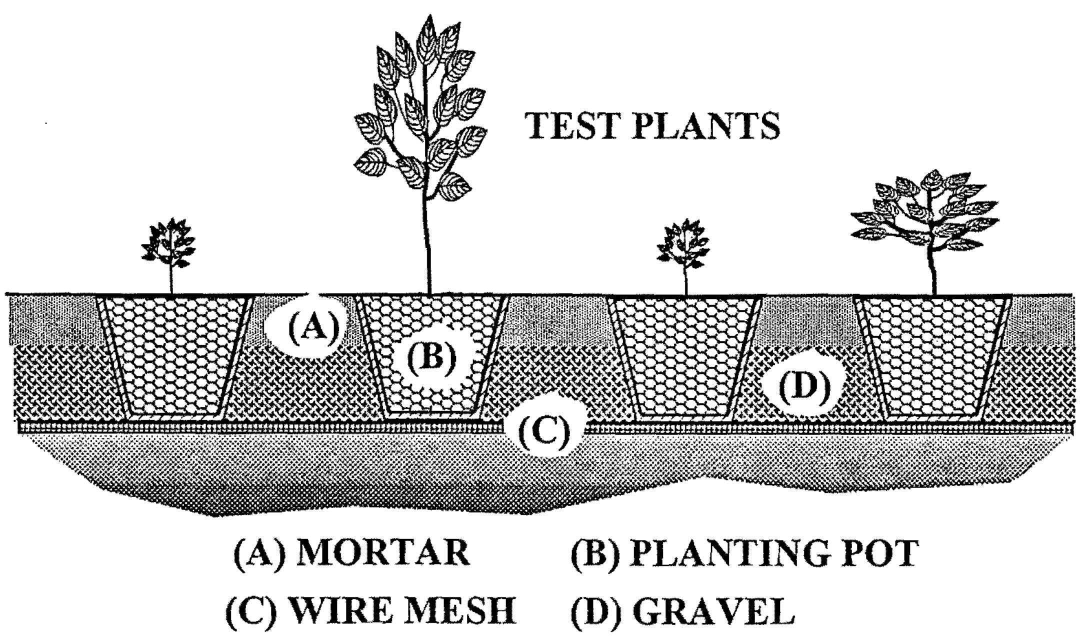


Figure 1 Setup for Test Plants

6-3 The thirteen 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
6) 28-inch Yellow Twig Dogwood
7) 38-inch Mulefat
8) 30-inch Alder
9) 38-inch Valley Elderberry
10) 60-inch Salt Cedar
11) 48-inch Black Willow
12) 24-inch Red Willow
13) 60-inch Mountain (Cocotte/Black) Willow

6-4 The ten 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)

6-5 Table 2 and Figures 2, 3, and 4 show the plant dimensions, plant density, and numbers of plants tested in the large flume tests. Table 2 shows the average dimensions and plant characteristics of the plants tested in the large flume. Table 3 shows the average dimensions and characteristics of the plants tested for drag force in the sectional flume. The range of heights of individual plants varied from the average height characteristics in Table 3 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.

Table 2 Plant Characteristics and Dimensions Tested in 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 psf
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 (medium)	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 3 Dimensions and Characteristics of Plants Tested for Drag Force

Plant/Runs	H(cm)	W_p(cm)	D_S(cm)	H' (cm)	E (N/m²)	# of 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

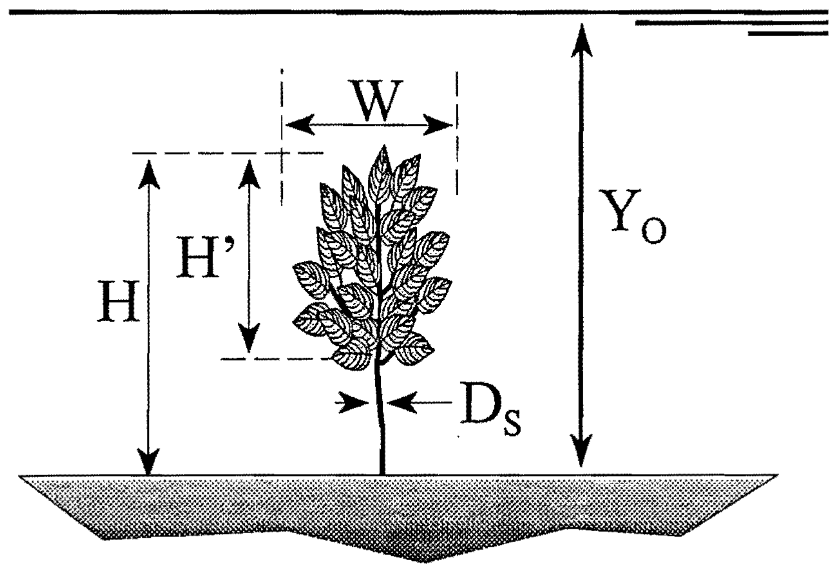


Figure 2 Plant Dimensions for Submerged Flow

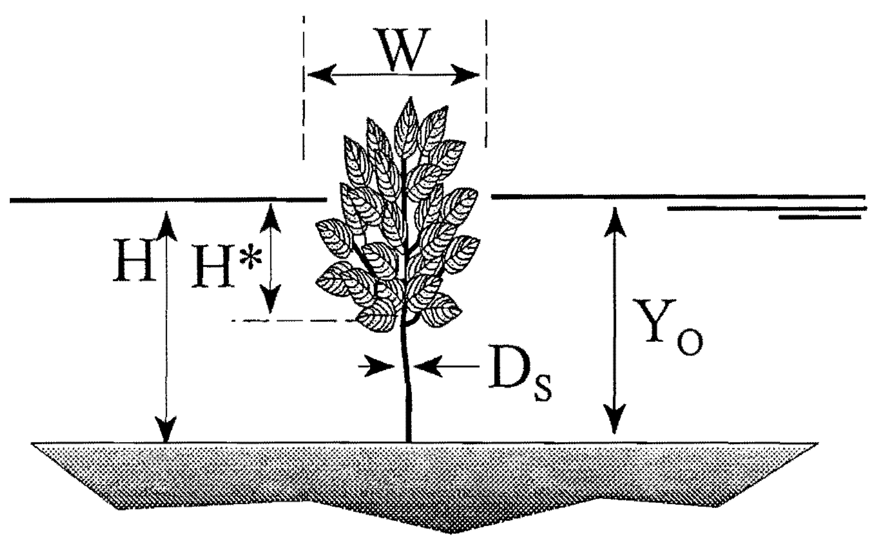


Figure 3 Plant Dimensions for Plants in Partially Submerged Flow

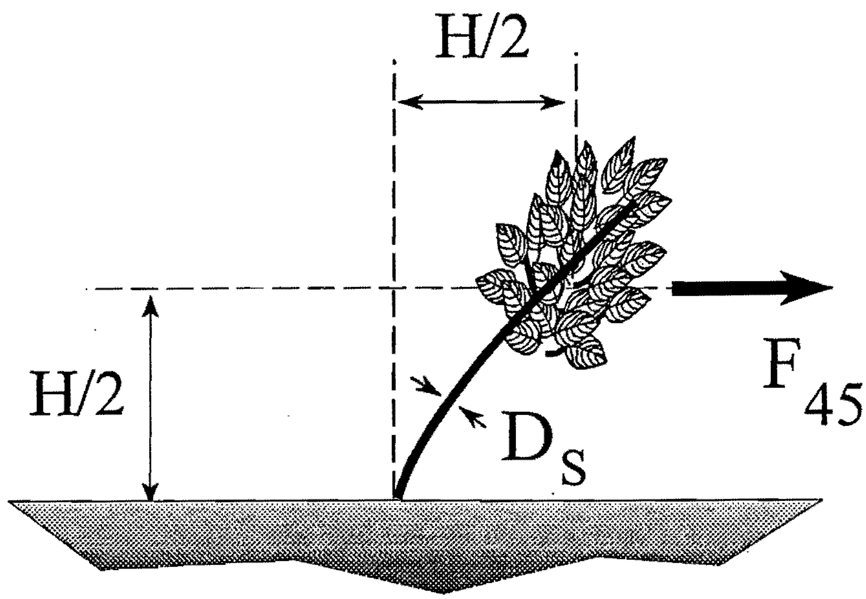


Figure 4 Plant Dimensions for Determining Stiffness

6-6 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 the modulus of elasticity of a plant stem (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).

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).

6-7 Plant stiffness or modulus of elasticity is one of the plant characteristics used in this study. E is 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) to half way up, H/2, the stem of the plant, and the stem is pulled, H/2, horizontally. The modulus is calculated using Equation 21, where I is the second area moment of inertia.

$$E = \frac{F_{45} H^2}{3 I} \quad where\ I = \frac{\pi D_S^4}{64} \tag{21}$$

6-8 M is the plant density in number of plants pèr unit area. M should not be confused with the M used by other researchers (Kouwne and Li, etc) to designate a relative plant density of number of plants /m² divided by 1 plant /m².

6-9 The cross sectional area, A_S, of the plant stems is used to calculate plant stiffness. The cross sectional area is the total area of the stems of an individual plant. A_S and the stem diameter D_S are measured at a distance of H/4 from the bed.

section 7 LARGE FLUME (RESISTANCE) TEST SETUP

7-1 The concrete floor under the test section of the large flume (Figure 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 their 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 4 and 5 containers per row) and anchored to the floor and fencing. A gravel bed with mortar cap(Figure 1 of Section 6) 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 istead 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 flumes west wall was adjacent to the downstream reach of the test section.

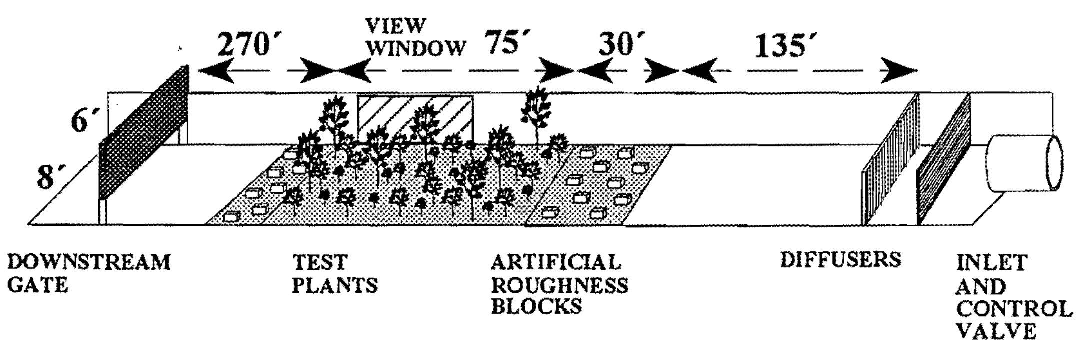


Figure 5 Sketch of Large Flume

7-2 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. To ensure that the blocks created the necessary velocity distribution, tests were conducted with velocity profiles at different locations to verify the spacing of the cinder blocks.

7-3 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 to protect the test plants during filling. It was found that several layers of stop logs had to be left in during testing, especially with low water depths, to maintain a constant velocity profile throughout the test section. At the downstream end of the flume, 300 feet downstream of the test section, a hydraulic gate was used to control flow depth. A second set of stop logs were later placed downstream to also control the flow depth and to decrease the time necessary to establish steady flow after each flow change.

7-4 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 Mapco 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.

7-5 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 and at the middle of the test section and just upstream of the test plant used to measure drag force.

7-6 A single plant, in the centerline of the flume and at station #25, 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. Using a Vishay Instrument Model P-350 Strain Indicator, the drag force produced by the individual test plant was then able to be determined. The platform 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. The strain gage was zeroed at the start of each series of runs, and the sensitivity of the strain gage was 200 micro-inches per inch per pound. Measurements were taken to the nearest micro-inch. The following section 9 of this report explains the mounting of the test plant in detail.

section 8 PROCEDURES FOR RESISTANCE TESTS

8-1 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.

8-2 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.

8-3 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 #25. The local velocity at the plant (plant approach velocity) was measured 2 inches upstream 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 stagnation 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 (for Phase I) were observed through the view window for soil movement, plant distortion, and plant failure.

8-4 The procedure to calculate the Manning's coefficient n for the plant resistance, 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 23 was the equation used to fit the backwater curve.

$$\frac{dy}{dx} = \left(\frac{S_o - S_f}{1 - F_r^2} \right) \tag{23}$$

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 the Manning's equation (Equation 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 24.

$$F_r = \frac{V}{\sqrt{g \cdot R_h}} \tag{24}$$

The total Manning's *n* was then iteratively solved using a trial and error process until the shape of the backwater curve predicted by Equation 23 was the same as the measured curve of the actual water surface. Figure 6 is an example of the backwater curve fit for a test run with a total Manning's *n* of 0.062.

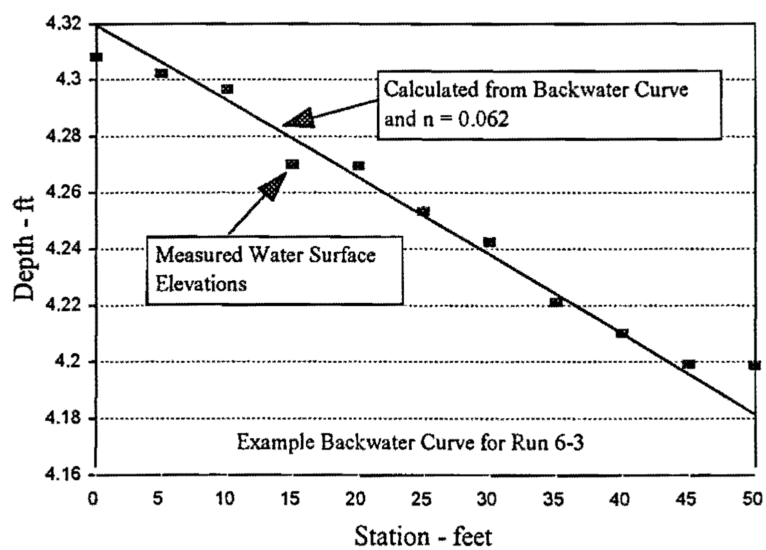


Figure 6 Example of the Fit of a Backwater Curve to Determine ***n***

8-5 From the total Manning's n, the value of n_b for the bed roughness and plant resistance was determined. This was done through a number of steps. First, the total n was converted to a Darcy-Weisbach friction factor, f, by Equation 25.

$$f^2 = \frac{n\sqrt{8g}}{1.486 \cdot R_h^{1/6}} \tag{25}$$

The coefficient of friction for the bed and plants, f_b, was determined using a correction for the effects of the flume walls and an assumption that the channel was rectangular. The coefficient of friction for the walls, f_w, was determined from Equation 26 regressed for this study to fit the correction figure presented in the ASCE Sedimentation Engineering Manual (1977).

$$f_w = 0.274367\left(\frac{R_E}{f}\right)^{-0.175092} \tag{26}$$

Where R_E is the Reynold's number. Equation 16 was a power fit regression with an r^2 of .9998. The friction factor for the bed, f_b, was then calculated with Equation 27.

$$f_b = f + \frac{2Y_o}{b}\left(f - f_w\right) \tag{27}$$

Where, b is the width of the channel, and Y_o is the flow depth. Manning's resistance coefficient for the bed roughness and plant resistance was calculated from the hydraulic radius R_b determined by Equation 28

$$\frac{R_b}{f_b} = \frac{R_w}{f_w} = \frac{R}{f} \tag{28}$$

Where R_b is the hydraulic radius for the bed and plants; R_w is the hydraulic radius for the walls; and R is the gross hydraulic radius. Equations 27 and 28 are from the

ASCE Sedimentation Engineering manual (1977) on side wall corrections. Finally, the Manning's coefficient n_b for the bed roughness and vegetation was converted from R_b from the Manning's equation (Equation 1).

8-6 The coefficient n_b is the resistance of both the bed roughness and the vegetation. Equation 29 was used to calculate the resistance coefficient n_{veg} for the net resistance of the vegetation.

$$n_{veg} = n_b - n_{base} \tag{29}$$

Where, n_{veg} is the Manning's coefficient for vegetation; n_b is the bed and vegetation resistance; 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.

section 9 SECTIONAL FLUME (DRAG FORCE) TEST SETUP

9-1 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 ft. by 3 ft. channel running perpendicular to the flume entrance. A baffle was placed at the entrance of the flume to straighten the incoming flow. A plexiglass observation window was also installed in the side of the flume.

9-2 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 1 ½ in. thick false deck out of smooth, painted plywood. The deck was bolted through the bottom of the flume and sealed with silicon caulk. Several one 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.

9-3 To attach the plants to the bottom, a beveled rubber grommet and wide flanged washers were used. The roots of the plants were cut of 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 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.

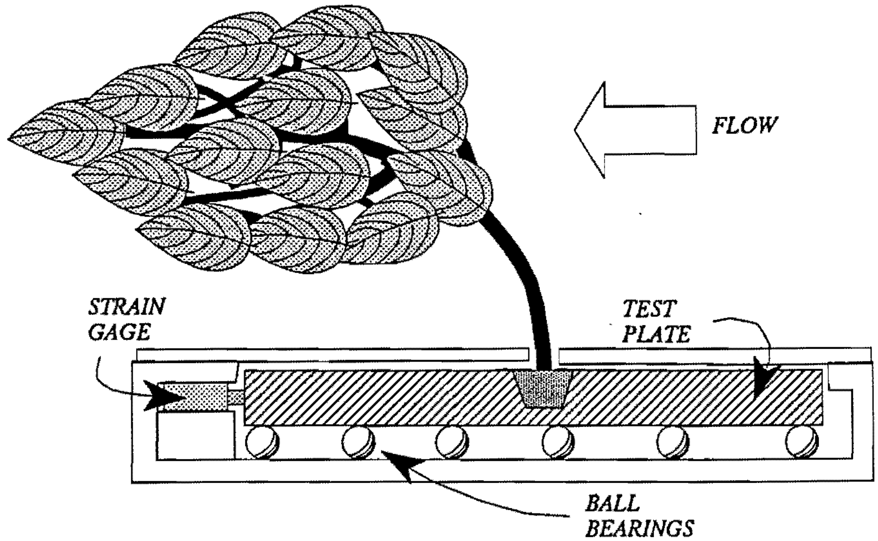


Figure 7 Test Setup to Measure Plant Drag

9-4 The test plant used to measure drag force used the same rubber grommet method, but was attached to a smooth aluminum plate (Figure 7) rather than the plywood floor. The plate was 6 inches wide by 12 inches long and 1 in. 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.

9-5 To assimilate the plate into the deck, a 6 ½ in. by 12 ½ in. rectangle was cut in the center of the floor along the centerline of the flume. Since the floor was 1 ½ in. thick, ½ in. 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 1 ½ in. 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.

9-6 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.

9-7 Elastic bands or springs were was 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. A sketch of this setup is shown in Figure 7.

9-8 Velocity measurements were made from a propeller type Ott Velocity Meter. Velocity measurements were taken just upstream of 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 10 PROCEDURES FOR DRAG FORCE TESTS

10-1 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 were 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.

10-2 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 ft. This allowed the flume to be completely filled and the strain gauge set to zero to compensate for any buoyancy effects.

10-3 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 very 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 uniform velocity profile occurred.

10-4 Each plant was subjected to a series of 10 runs. Each run was at an increasing velocity, ranging from approximately 0.25 to 8 ft/sec. During each run, the velocity directly upstream of 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. Video tapes were taken to allow for more detailed observation of the plants at a later time.

10-5 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 fashion.

section 11 RESULTS FOR THE RESISTANCE TESTS

11-1 There were eight test series for Phase I and fourteen test series for Phase II that were completed using different plants types, plant heights, plant spacings, and combinations of plant types. The first Phase I series and the first Phase II series were performed on only the bed, without vegetation, to determine the bed roughness. A Manning's 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 for the mortar bed of Phase II. The data sheets and backwater curve fits for each test run are in Volume 2, Appendix A for Phase I and in Appendix B for Phase II.

11-2 Tables 2 and 3, of section 6, list the dimensions, characteristics, and plant densities of the plants tested. Tables 4 and 5 present the results from the submerged testing of eleven different plants all conducted with a single plant type and plant size for each test series.

11-3 Table 6 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. Tables 7, 8, 9, and 10 present the results from the submerged tests of five different plant groups or ecosystems consisting of combinations of multiple plant types and sizes.

Table 4 Summary of Results for Submerged Tests

Plant Type	Flow Depth Yo ft	Mean Velocity V fps	Energy Slope S	Plant Density M 1/ft²	Hydr Radius Rh ft	Reynolds 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	0.044
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	0.00331	0.529	2.205	6.33e+05	0.154	0.046

Table 5 Summary of Results for Submerged Tests

Plant Type	Flow Depth Yo ft	Mean Velocity V fps	Energy Slope S	Plant Density M 1/ft²	Hydr Radius Rh ft	Reynolds Number Re	V*/V	Manning's n
Large Dogwoods	4.143	1.059	0.00110	0.113	4.036	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 Summary of Results for Patially Submerged Tests

Plant Type	Flow Depth Yo ft	Mean Velocity V fps	Energy Slope S	Plant Density M 1/ft²	Hydr Radius Rh ft	Reynolds 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 7 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
5-3	0.170	1.610	2.679	0.038			0.00384	0.046
5-2	0.170	4.558	2.911	0.029			0.00118	0.045
5-4	0.170	2.320	3.158	0.036			0.00342	0.047

Table 8 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 bed
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		0.00	0.00103	0.051
6-4	0.060	3.518	2.594	0.030		0.00	0.00119	0.043
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		0.0010665	0.106
7-2	0.230	4.411	1.496	0.052			0.0010211	0.083
7-3	0.230	3.766	2.048	0.047			0.0017338	0.071
7-4	0.230	3.301	2.772	0.050			0.0039484	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	0.0018667	0.119
8-2	0.390	4.397	1.714	0.070	1.28	1.10	0.0024329	0.113
8-3	0.390	4.517	2.380	0.065	1.64	1.70	0.0039761	0.106
8-4	0.390	3.901	1.750	0.075	1.40	1.35	0.0031476	0.116
8-5	0.390	3.650	1.860	0.075			0.0037216	0.114
8-6	0.390	3.826	1.750	0.065	1.51	1.50	0.0023952	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			0.0009863	0.135
9-2	0.160	4.365	1.400	0.070			0.0016314	0.113
9-3	0.160	3.515	1.714	0.068			0.0026694	0.102
9-4	0.160	2.999	2.038	0.072			0.0047546	0.103

Table 9 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 bed
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
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

Table 10 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 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			0.0028276	0.142
13-9	0.450	4.639	1.725	0.083			0.0033481	0.137
13-10	0.450	4.194	1.967	0.080			0.0043152	0.127
13-11	0.450	4.534	2.936	0.062			0.0054942	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			0.0037913	0.093
Run 14-2 was with36 mountain willows (5 stems each) (SUBMERGED) in a 400 ft² test bed. NO LEAVES								
14-2	0.450	4.515	1.207	0.075			0.0013618	0.122

11-4 Figure 8 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 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-Prantl 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.

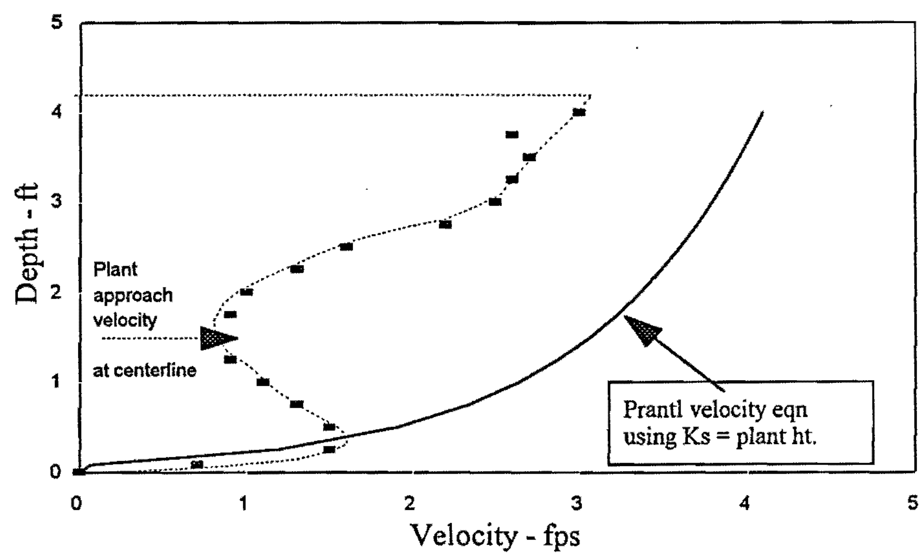


Figure 8 Example Velocity Profile for a Test Run of Dogwoods

11-5 The test runs were both video taped and photographed. It was obvious that the flow resistance was influenced by the flow blockage and roughness of the leaf mass of the shrubs. A very important observation was that the plant 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 can not be considered a rigid area of blockage.

11-6 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, i.e. gravel, that was being transported by the flow.

II-7 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 was eroded. The velocities were sufficient to transport and move the largest sizes of gravel along the surface of the bed.

II-8 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 3 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.

II-9 The following Figures 9 through 14 demonstrate the effect of velocity on plamt deformation, sediment transport, and scour.

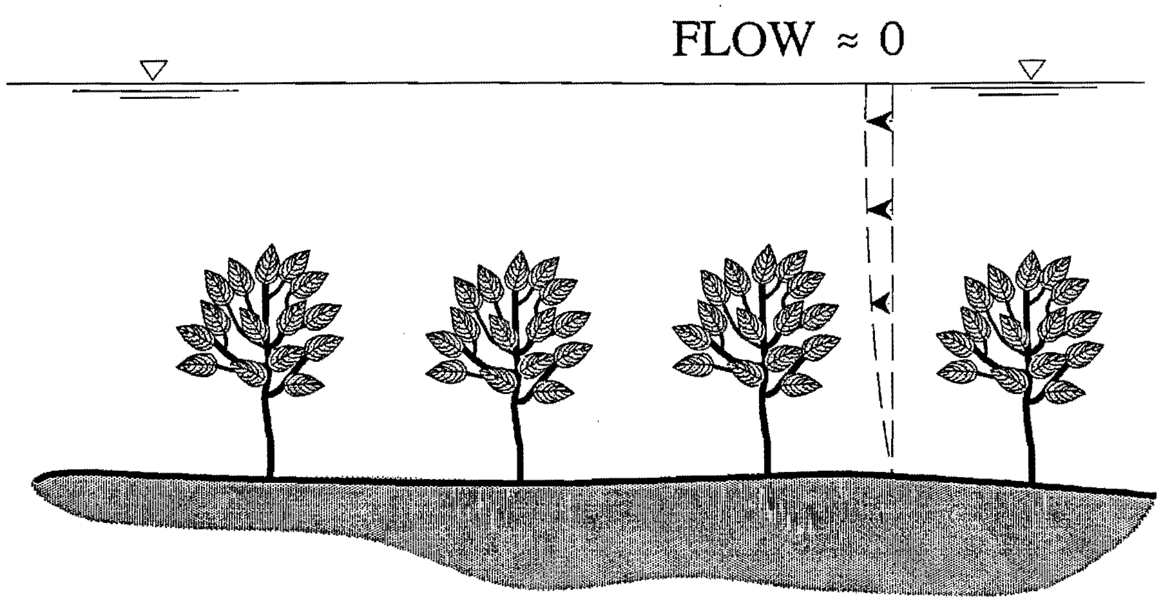


Figure 9   Test Plants at Zero Flow

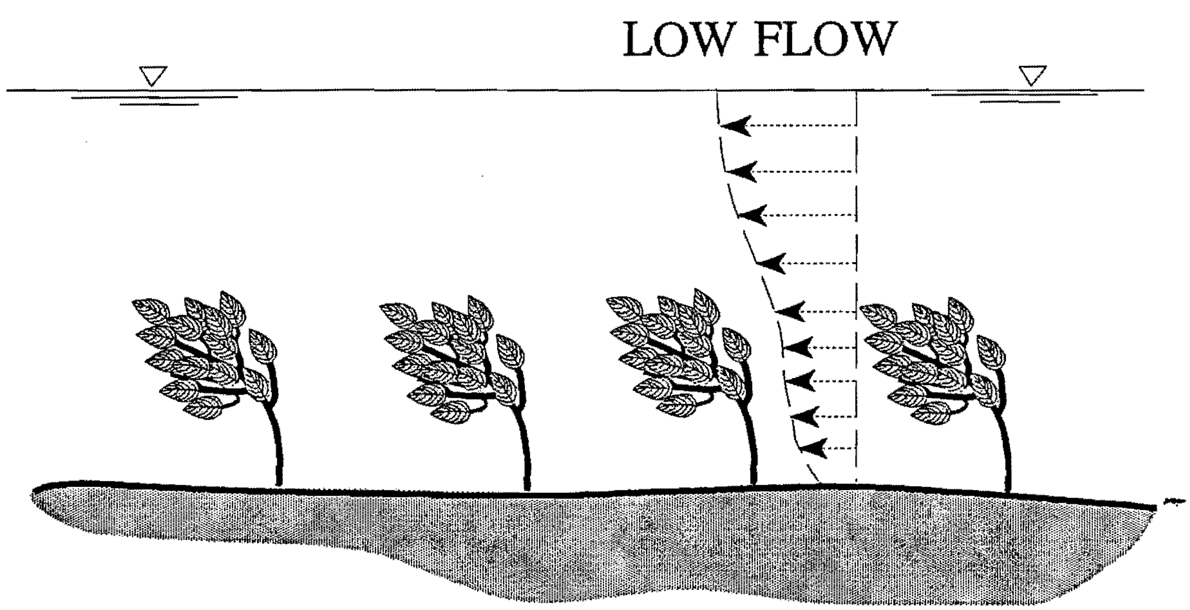


Figure 10   Test Plants at Low Flow

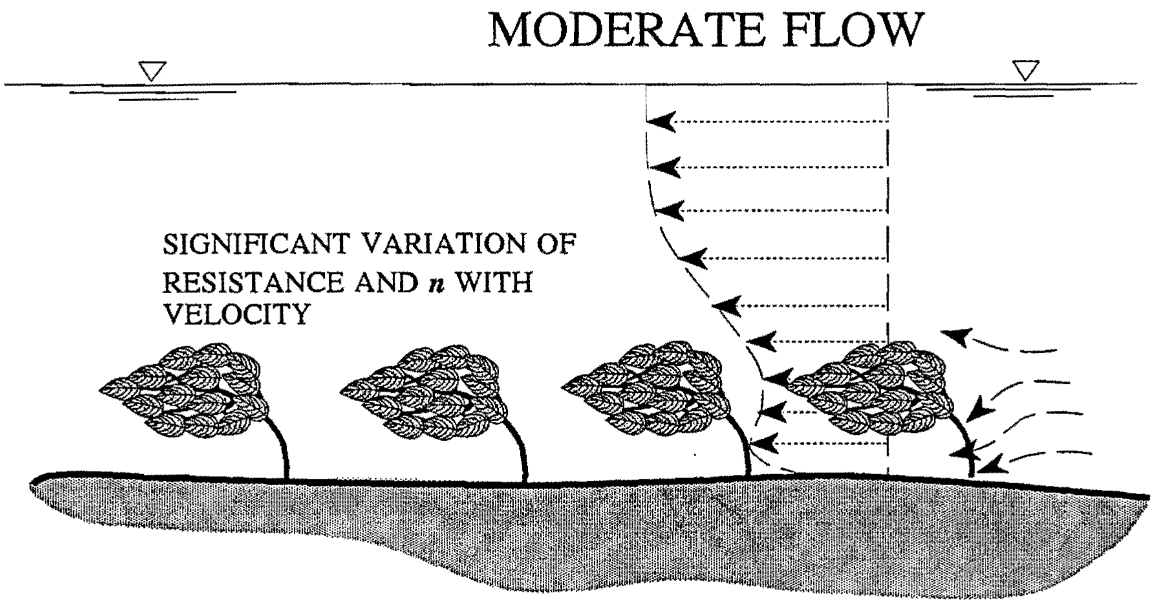


Figure 11 Test Plants at Moderate Flow

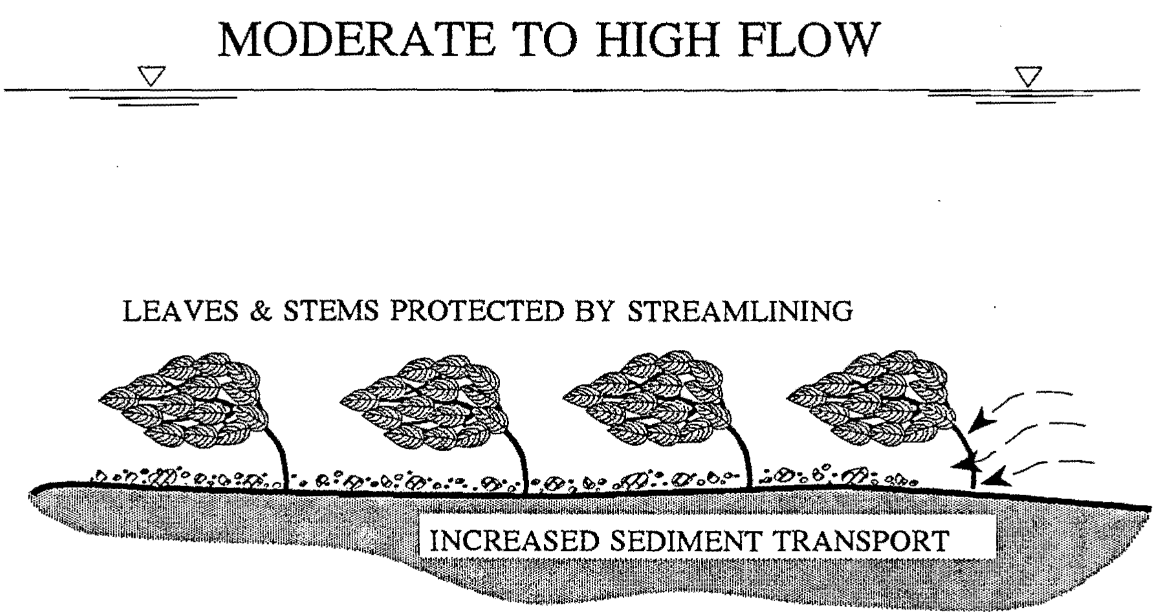
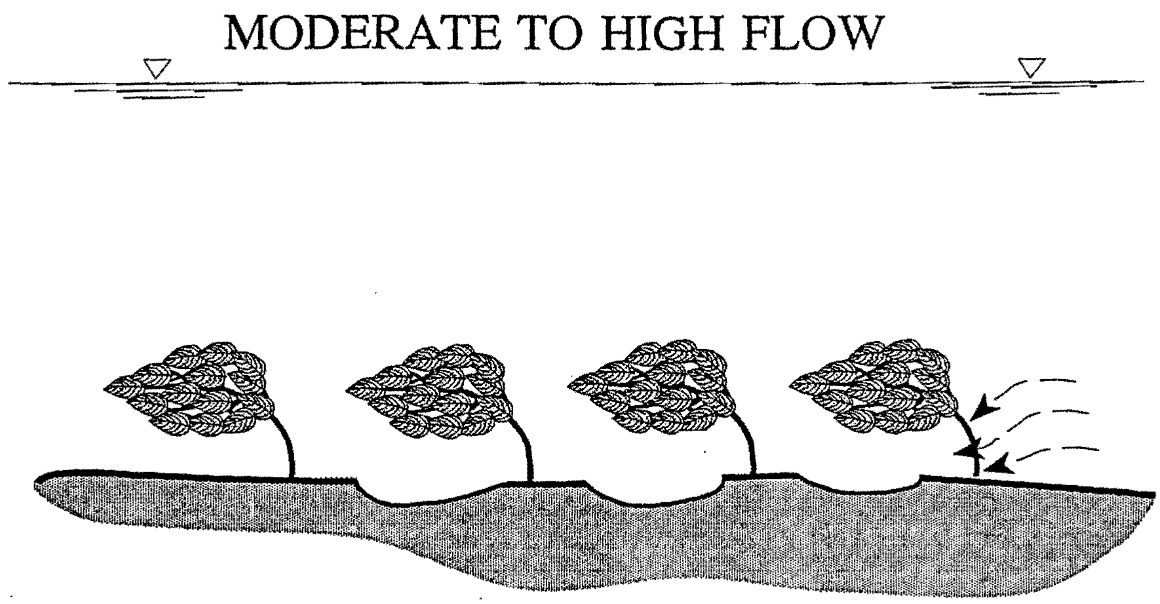
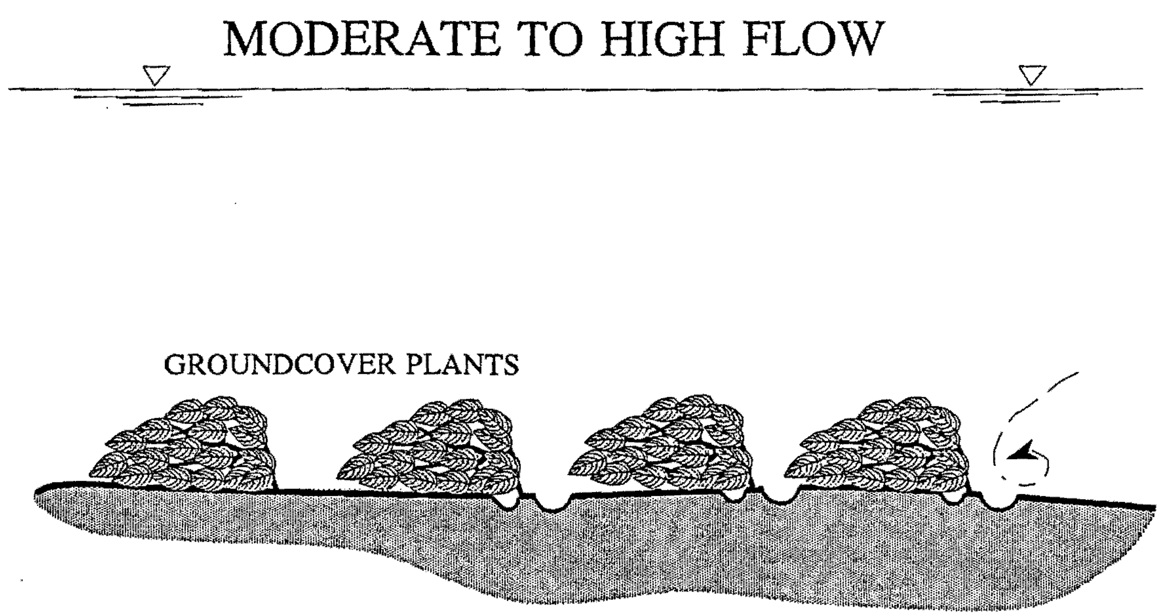


Figure 12 Test Plants with Sediment Transport



LOCAL EROSION IN OPEN AREAS
Figure 13 Test Plants with Local Erosion



VORTEX EROSION AT STEMS
Figure 14 Test Plants with Stem Erosion

section 12 RESULTS FOR THE DRAG FORCE TESTS

12-1 Table 11 shows the tabulated values for the measured drag force on the test plants in the large flume for the Phase II testing.

12-2 Table 12 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.

12-3 Figure 15 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 resistance coefficients determined in the large flume tests.

12-3 Figure 15 also shows a linear relationship between drag force and plant velocity. Test data from four different Dogwood plants are included in Figure 15. 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.

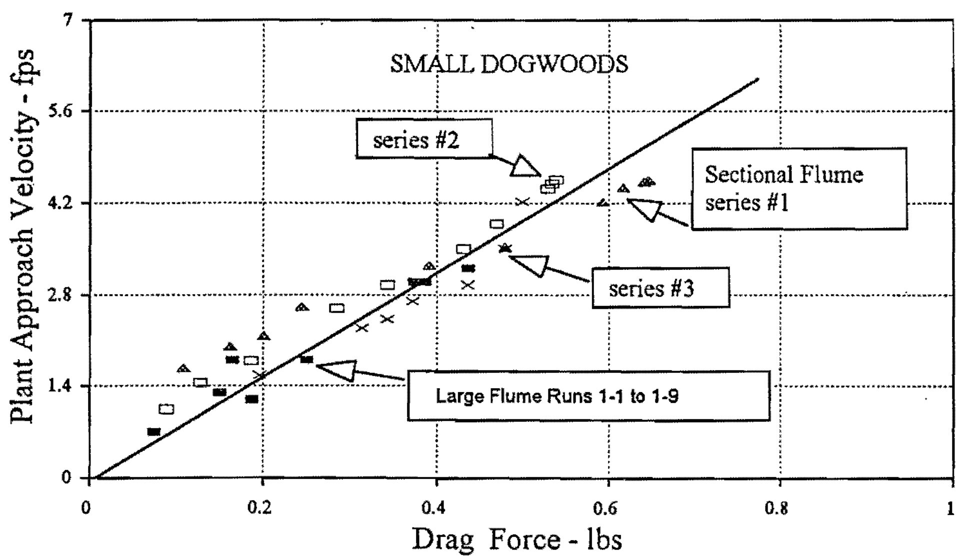


Figure 15 Plant Approach Velocity vs. Drag Force

Table 11 Drag Force versus 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 12 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

section 13 ANALYSIS OF DRAG FORCE FOR SECTIONAL FLUME

13-1 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. The leaf mass changed with velocity and became more streamlined with increased velocity. This observation explains the significant decrease in resistance with velocity. It is important to note that the leaf mass can not be considered a rigid area of blockage, and that any approximation of a constant resistance coefficient to predict stage will be invalid . This can be shown by considering the basic drag force equation , Equation 30.

$$F_D = \frac{\rho \, C_D \, A \, V^2}{2} \tag{30}$$

If the plant resistance were constant with increasing velocities, a plot of velocity versus drag force would appear as a smooth exponentially increasing curve. However, since the resistance decreases with increasing velocity, due to the plants tendency to streamline, the plot appears linear. A typical plot of velocity vs. drag is shown in Figure 16, 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 plants drag coefficient becomes constant.

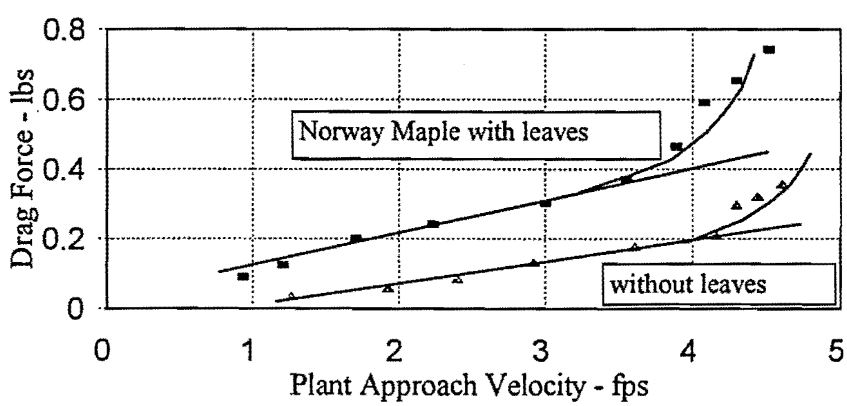


Figure 16 Drag Force versus Velocity

13-2 Over 100 tests were conducted in the sectional flume of ten different plant types, and over 20 tests were conducted in the large flume of four plant types to study drag force. Tables 11 and 12 of Section 11 present a summary of the results, and Appendix C of Volume 2 of this report contain the test data.

13-3 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 modulus of elasticity E, and the area moment of inertia of the plant stem I. Equation 31 is the relationship between the drag force F_D on a single plant and the geometry and characteristics of the plant. The regression analysis had a regression coefficient of R^2=89% and a maximum scatter of predicted values to actual of 16%.

$$\frac{F_D H'^2}{EI} = 100.24 \left(\frac{H}{H'}\right)^{1.45} \left(\frac{\rho \, TL_A V_P^2}{E D_S^2}\right)^{0.8} \left(\frac{H'}{D_S}\right)^{0.15} \left(\frac{H'^2}{TL_A}\right)^{0.89} \tag{31}$$

The parameters of Equation 31 then represent the ratio of drag force to stiffness or bending force, the ratio of effective plant height, the ratio of bending resistance, the ratio of plant flexibility, and the ratio of plant blockage. The total leaf area TL_A is determined by multiplying the total number of leaves by the average leaf area. The modulus of elasticity E is determined (Equation 21 of Section 6) by measuring the force F_{45} to bend the plant by an angle of 45 degrees. The 45 degree bending angle is measured from the base of the plant stem to the center of the leaf mass (see Figure 4 of Section 6).

section 14 ANALYSIS OF RESISTANCE BY KOUWEN AND LI'S METHODS

14-1 Tables 4 and 5 of Section 11 contain the results from the resistance testing for submerged flow in the large flume. It has been proposed by other researchers that the equations and methods developed by Kouwen and Li to predict resistance of flexible grasses could be applied to plants such as shrubs and riparian plants. The method and equations of Kouwen and Li's (see Sections 2-8 and 2-9 of this report) were analyzed with the test data and plant characteristics from this study. Their equations and suggested equation exponents resulted in predicted values of resistance that poorly fit the measured data. A regression of predicted to measured resistance resulted in a regression fit 160% scatter with a regression coefficient, R^2, of less than 30%.

14-2 Their equations were then compared to the test data to determine the optimum coefficients to give a better fit with data. The best fit for measured data with predicted values from their equations was with the constants a=0.1807 and b=1.268. The fit of the equations resulted in an improved R^2=43% and a scatter of data of over 90%. Figure 17 shows a comparison of calculated or predicted resistance to the actual measured values with the improved exponents.

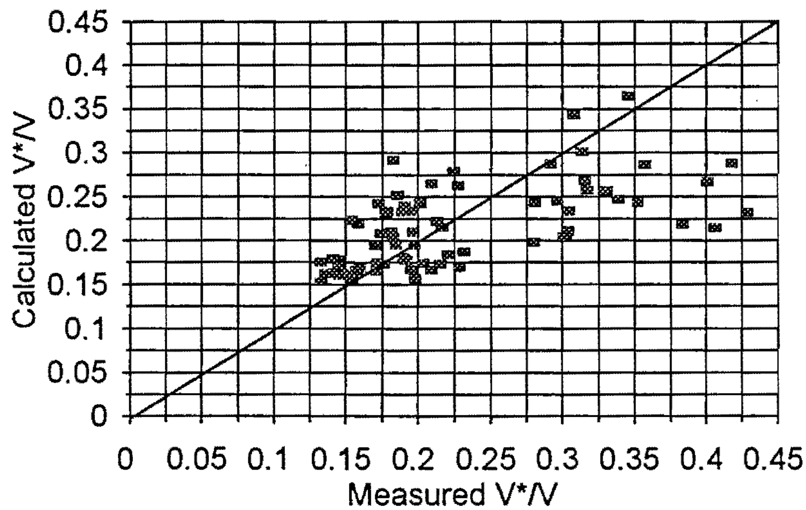


Figure 17 Comparison of Kouwen and Li's Method with Test Data

14-3 The equations of Kouwen and Li were developed for grasses with high densities. Their methodology does not account for flow through or around individual plants. An attempt was made to modify their equations to replace the relative density M' with the parameter MxA. The density M used in this study is not a relative density but the number of plants per unit area of bed. The blockage area of an individual plant is A. An analysis of the modified equations (Equations 32 and 33) resulted in a fit of data of R^2=69 with a scatter of 41%. The best fit was with the exponents a=-0.08 and c=1.176, Figure 18.

$$n_b = \frac{y_n^{1/6}}{\sqrt{8g\left[-0.08 + 1.176 \cdot \log\left(\frac{y_n}{k}\right)\right]}} \tag{32}$$

$$k = 0.14 \cdot h \cdot \left(\frac{\left(\frac{M\,A\,E\,I}{\gamma\; y_n\; S}\right)^{0.25}}{h}\right)^{1.59} \tag{33}$$

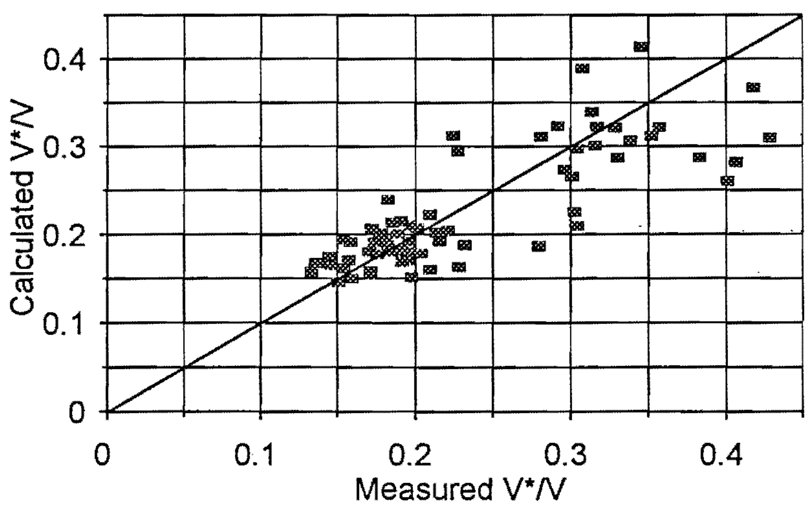


Figure 18 Comparison of Modified Kouwen and Li Equations

section 15 DEVELOPMENT OF RESISTANCE METHODOLOGY

15-1 Kadlec (1990) presented a hypothesis that the flow resistance from vegetation can be thought of as the result of the total forces, F_B, produced by vegetation on the channel bottom. This hypothesis is the major premiss 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 (Equation 20) produced by the plants. The plant density P_d can be calculated by Equation 21 and be equated to the average plant spacing P_S as shown in Equation 21. 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 average drag force times the plant density (Equation 34).

$$\tau_O = \sum \frac{F_D}{area} = F_D M \tag{34}$$

Where τ_o is the plant shear stress on the channel bottom, M is the plant density in numbers of plants per unit square foot, and F_D is the drag force produced by an individual plant.

The shear velocity V* is related to shear stress by Equation 2, and a commonly used resistance parameter that is associated with shear stress is V*/V (Equation 3).

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

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

The shear velocity and shear stress can then be related to drag force by Equation 35,

$$V^* = \sqrt{\frac{\tau_O}{\rho}} = \sqrt{\frac{F_D M}{\rho}} \tag{35}$$

where the drag force F_D is defined by Equation 30. Vp is the velocity or the approach velocity to the plant. The drag coefficient CD should then be related to the resistance by Equation 36, where V_p is related to the mean velocity V.

$$F_D = \frac{\rho\, C_D\, A\, V_p^2}{2} \tag{30}$$

$$C_D \propto \frac{2\,(V*/V)^2}{A \cdot M} \tag{36}$$

However, the relationship of Equation 36 can not be directly related to flow resistance because the blockage area and shape of the plant vary as the plant bends, and because V_p is not always equal to V.

15-2 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. 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.

$$\frac{V^*}{V} \text{ or } C_D = f\left(\frac{F_I}{F_B}, \frac{Y}{H}, MA, R_E\right) \tag{37}$$

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

$$\frac{F_I}{F_B} = \frac{\rho\, V^2 A}{E A_S} \tag{38}$$

Where A is the blockage area of an individual plant, E is the modulus of elasticity 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 (Equation 22) is determined from the stem diameter D_S that is measured at a height of H/4 from the base of the plant.

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

$$R_E = \frac{V R_h}{\nu} \tag{39}$$

section 16 RESISTANCE FOR SUBMERGED FLOW

16-1 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_O/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 resistances V^*/V from 0.13 to 0.43, and a range of resistances n from 0.04 to 0.15.

16-2 The measured plant resistance was corrected so that the resistance included the resistance caused by the plants and the bed resistance below the plants. The effect or resistance of the flume walls was corrected for by the procedures discussed in Section 8. To further correct the resistance coefficients to include only plant resistance, 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 resistance coefficients predicted and reported in this study are then for the effects of plant and the underlying bed.

16-3 The resistance data reported in Tables 4 and 5 of Section 11 were then analyzed to determine the regression of the variables of Equation 37. The regression analysis found that a log relationship gave a poor fit of data while a power relationship had very good results. Equations 39 and 40 were found to fit the test data with a regression coefficient of R^2= 96% and a maximum scatter of 15% for predicted values of V^*/V with measured values. A regression coefficient of R^2= 93% and a maximum scatter of 20% were found for predicted values of n with measured values.

$$\frac{V^*}{V} = 0.326 \left(\frac{E A_s}{\rho V^2 A}\right)^{0.128} \left(\frac{H}{Y_O}\right)^{0.187} (MA)^{0.182} \left(\frac{1}{R_E}\right)^{0.0828} \qquad \textbf{(40)}$$

$$n = 0.039 \left(\frac{E A_s}{\rho V^2 A}\right)^{0.141} \left(\frac{H}{Y_O}\right)^{0.175} (MA)^{0.191} \left(\frac{\nu}{V R_h}\right)^{0.0155} \qquad \textbf{(41)}$$

16-4 It is important to note that the plant characteristics H, A, and A_S are for un-disturbed or for plants that have not been distorted by flow. During Phase 1 and Phase 2 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 40 and 41 are then for application with only submerged flow defined by $Y_O > 0.8(H)$.

16-5 A is the effective plant area or total blockage to flow direction 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 un-distorted 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.

16-6 Equations 40 and 41 also include 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.

16-7 The analysis of data and the regression fit of Equations 40 and 41 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 elasticity must be used.

16-8 Figures 19 and 20 show the comparison of predicted resistance coefficients (Equations 40 and 41) 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 increased blockage area and density, and decrease with increased depth and velocity.

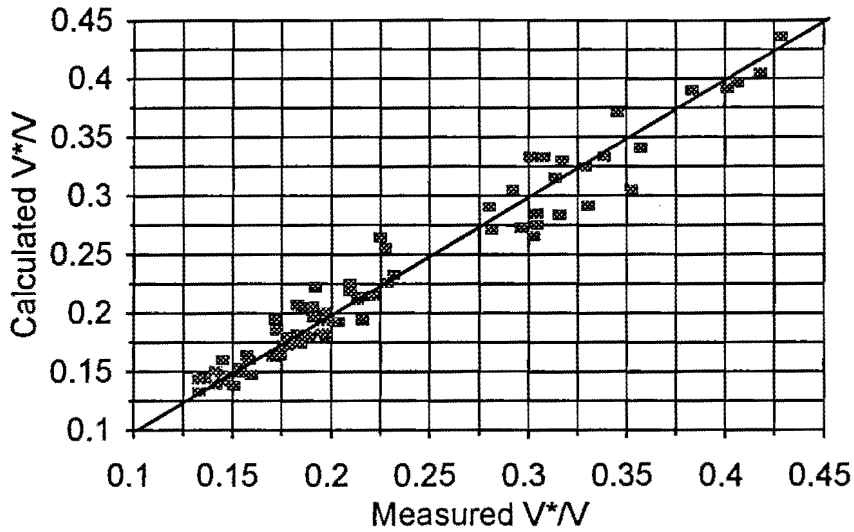


Figure 19 Comparison of Predicted with Measured Resistance for Submerged Flow

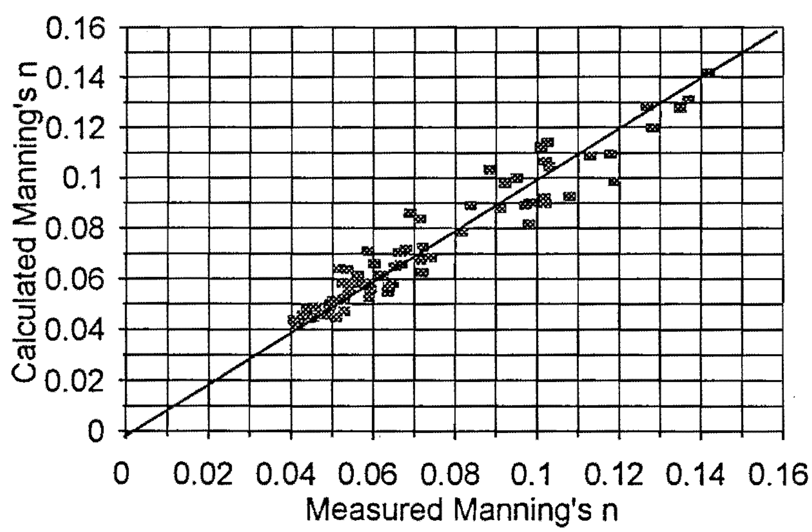


Figure 20 Comparison of Predicted with Measured Resistance for Submerged Flow

section 17 RESISTANCE FOR PARTIALLY SUBMERGED FLOW

17-1 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 4 different plant types. The same procedures and analysis used in Section 16 for submerged flow was repeated for partially submerged flow.

17-2 The resistance data reported in Table 6 of Section 11 were then analyzed to determine the regression of the variables of Equation 37. The regression analysis again found that a log relationship gave a poor fit of data while a power relationship had very good results. Equations 42 and 43 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.

$$\frac{V^*}{V} = 4.5x10^{-5} \left(\frac{E A_S}{\rho V^2 A*} \right)^{0.224} (MA*)^{0.0592} \left(R_E\right)^{0.530} \tag{42}$$

$$n = 2.2x10^{-6} \left(\frac{E A_S}{\rho V^2 A*} \right)^{0.242} (MA*)^{0.0623} \left(\frac{\nu}{V R_h} \right)^{0.662} \tag{43}$$

17-2 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 44 if the geometry of the plant and leaf mass haven't been measured.

$$A^* = \left[Y_O - (H - H')\right] W \tag{44}$$

17-3 The regression analysis again showed that plant stiffness or flexibility must be considered, and the modulus of elasticity E had to be included. The parameter Y_O/H was found to have little effect and was not used. Figure 21 shows a comparison or fit of Equation 42 with measured values of resistance.

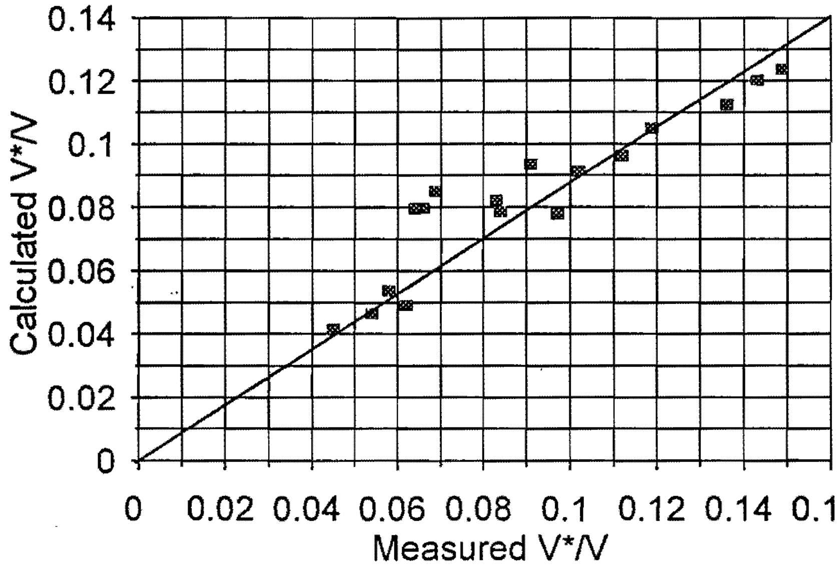


Figure 21 Comparison of Predicted to Measured Resistance for Partially Submerged Flow

17-4 It is important to again note that the plant characteristics H, W, A*, and A_S are for un-disturbed or for plants that have not been distorted by flow. During Phase 1 and Phase 2 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 42 and 43 are then for application with only partially submerged flow defined by $Y_O < 0.8(H)$. 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 18 RESISTANCE FOR MULTIPLE PLANT GROUPINGS

18-1 The analysis for Equations 40 through 41 of submerged and partially submerged flow, used resistance data from tests of uniform sizes and type 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 tested have been presented in Tables 7 through 10 of Section 11.

18-2 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 sized and types of plants. It was found that by using a weighted average for plant characteristics and dimensions produced good correlation with the equations for submerged and partially submerged flow.

18-3 The application of the resistance equations uses plant dimensions for an average plant. 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 elasticity 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}.

$$M_{total} = \sum M_i \tag{45}$$

Where the average characteristics are then:

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

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

18-4 Figure 22 shows the application of the equations for submerged and partially submerged flow with the measured resistance for the 5 multiple plant groupings. The figure shows an acceptable correlation with a maximum scatter of 20%.

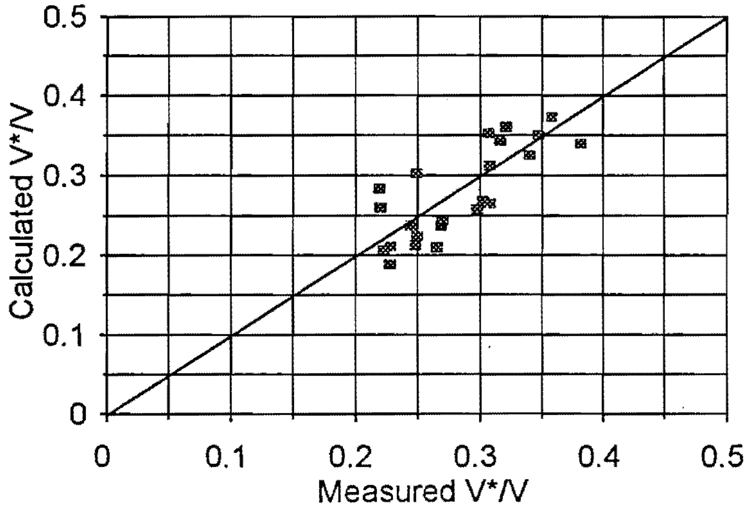


Figure 22 Comparison of Predicted with Measured Resistance for Multiple Plant Groupings

section 19 APPLICATION AND EXAMPLE OF METHODOLOGY

19-1 Equations 40 through 43 were based on the premise that resistance can be related to the total drag force produced by individual plants. If the premise and methodology are correct, it should be possible to then theoretically calculate (Equation 46) the drag force of a plant based on the predicted resistance. Figure 23 shows the comparison of the calculated drag forces with the drag forces measured during the flow tests in the large flume. It should be noted that it was more difficult to measure accurate drag forces in the large flume, because of the movement and deposition of the plant soil during testing. However, Figure 23 still shows an acceptable correlation with a 1:1 fit.

$$F_D = \frac{\rho V^{*2}}{M} \qquad (46)$$

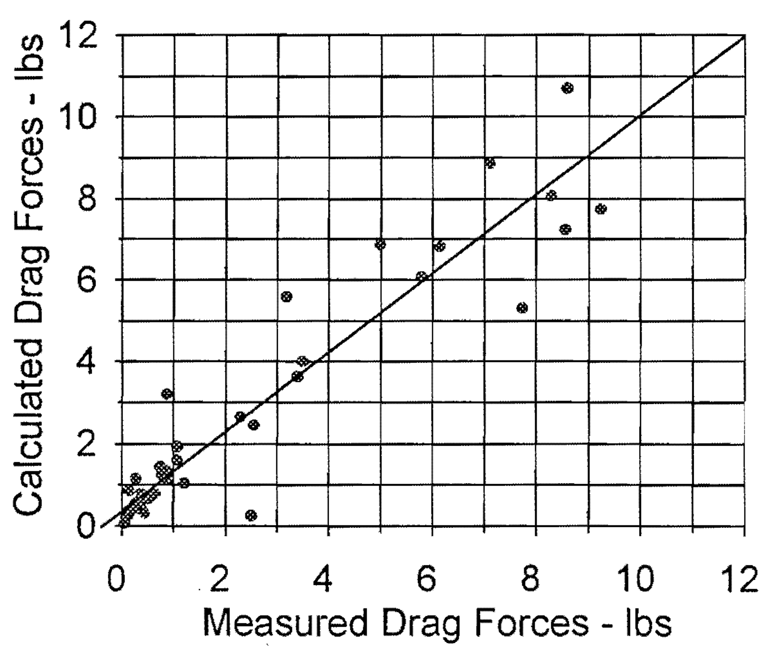


Figure 23 Comparison of Calculated Drag Force with Measured Drag Force

19-2 Several field studies were conducted in 1995 by Dr. Gary Freeman of the Waterways Experiment Station. The studies were made of the Bigwood and Henry's Fork rivers in Idaho, and the Big Cottonwood creek in Utah. All of the flow data was taken with partially submerged plants. Table 13 shows the measured plant dimensions, measured flow resistance, and the predicted resistance based on Equations 42 and 43 of this study. There is a good correlation for the predicted resistance with the resistance measured from the field studies. The only run that has questionable results is run *BCW-cha*. The measured resistance for this run was a Manning's n of 0.33 which was much larger than for other measured locations in the Big Cottonwood. This location also involved a very high density of plants compared to the other locations. A small variation in the measured density M will produce predicted values that have a much better correlation.

Table 13 Calculated Resistance Versus Measured Field Data

	Bigwood	BCW 1	BCW cha	BCW fp	HF 1-2	HF 1-2	HF 2
E (lb/ft²)	9.40e+06	4.18e+07	4.18e+07	4.18e+07	2.09e+07	2.09e+07	2.09e+07
M (#/ft²)	0.133	1.141	2.893	0.786	1.332	3.375	0.917
V (ft/s)	0.800	0.240	0.140	0.380	0.420	0.650	0.650
Yo (ft)	1.673	0.951	0.951	0.951	1.115	1.115	1.280
Ds (ft)	0.072	0.068	0.068	0.062	0.071	0.071	0.083
Ds (in)	0.866	0.819	0.819	0.740	0.850	0.850	1.000
# stems	7	7	7	7	6	6	6
As (ft²)	0.029	0.026	0.026	0.021	0.024	0.024	0.033
H (ft)	5.000	3.000	3.000	3.000	3.000	3.000	3.000
A (ft²)	0.121	0.065	0.065	0.059	0.079	0.079	0.107
Re	121,689	20,759	12,109	32,868	42,591	65,915	75,608
pV²A/EAs	5.57e-07	6.78e-09	2.31e-09	1.88e-08	5.47e-08	1.31e-07	1.28e-07
Yo/H	0.335	0.317	0.317	0.317	0.372	0.372	0.427
MA	0.016	0.074	0.188	0.046	0.105	0.267	0.098
Re	121,689	20,759	12,109	32,868	42,591	65,915	75,608
V*/V	0.42	0.48	0.49	0.47	0.45	0.49	0.50
f	1.40	1.85	1.89	1.80	1.62	1.94	2.02
n calc	0.12	0.12	0.13	0.12	0.12	0.13	0.14
n meas	0.11	0.08	0.33	0.14	0.18	0.14	0.14

Measured data from field survey taken Dr. Gary Freeman (W.E.S.)

Bigwood River, Idaho - Willows

Henry's Fork River, Idaho (HF) - Willows and Rose Bushes

Big Cottonwood Creek, Utah (BCW) - Mountain (Black) Willows

19-3 Table 14 is an example that demonstrates the use of Equations 40 and 42 for predicting flow resistance due to a combination or a multiple plant grouping. The example also shows the steps necessary to calculate a stage discharge relationship using an iterative solution of guessing the depth and then comparing with the calculated depth based on the predicted resistance.

Table 14 Example of Predicting Vegetation Resistance and Flow Depth

Find the resistance and depth of flow for a flood plain that is 80 feet wide and covered with a combination of dogwoods and willows. The flow across the flood plain is 1200 cfs. The slope of the plain was 0.002.
The density of water is 1.94 slug/ft^3 and the dynamic viscosity is 1.25E-5 ft^2/s.

In a sample plot of 20 feet by 20 feet, there were 40 willows and 20 woods.
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 dogwoods were: a stem diameter of 5/8" with 2 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 5 lbs necessary to bend a representative stem to 45 degrees.

Willows:		Dogwoods:	
H (ft) =	4	H (ft) =	4
W (ft) =	3	W (ft) =	3
H" (ft) =	3	H" (ft) =	3
D_s (ft) =	0.042	D_s (ft) =	0.052
# Stems =	5	# Stems =	2
calc A_s (ft^2) =	0.007	calc A_s (ft^2) =	0.004
calc A (ft^2) =	9.000	calc A (ft^2) =	9.000
Fb (lbs) =	3.000	Fb (lbs) =	5.000
calc I (ft^4) =	1.48e-07	calc I (ft^4) =	3.61e-07
calc E (lb/ft^2) =	1.08e+08	calc E (lb/ft^2) =	7.38e+07
Plants/400 ft^2 =	40	Plants/400 ft^2 =	20
calc M (1/ft^2) =	0.100	calc M (1/ft^2) =	0.050

calculate Average Plant:	
M_{total} =	0.150
Mi/M_{total} willow =	0.667
Mi/M_{total} salt c. =	0.333
H_{avg} (ft) =	4.000
W_{avg} (ft) =	3.000
H''_{avg}(ft) =	3.000
$D_{s\ avg}$ (ft) =	0.045
$A_{s\ avg}$ (ft^2) =	0.006
A_{avg} (ft^2) =	9.000
I_{avg} (ft^4) =	2.19e-07
E_{avg} (lb/ft^2) =	9.67e+07

assume that plants are submerged (Y_o>4.67 ft) and for a wide channel $R_h = Y_O$

guess depth Y_o (ft) =	10	8	6.8
width (ft) =	80	80	80
flow (cfs) =	1200	1200	1200
slope =	0.002	0.002	0.002
calc flow area (ft^2) =	800	640	544
calc V (fps) =	1.500	1.875	2.206
calc R_h (ft) = Y_O =	10	8	6.8
calc V* (fps) =	0.803	0.718	0.662
calc V*/V =	0.535	0.383	0.300

calculate resistance:			
$[E A_s] / [\rho V^2 A]$ =	14684.5	9398.1	6790.1
$[H/Y_o]$ =	0.400	0.500	0.588
[M A] =	1.35	1.35	1.35
[Re] =	1,200,000	1,200,000	1,200,000
therefor V*/V =	0.311	0.306	0.303
n =	0.08	0.08	0.07
calc V* =	0.466	0.574	0.668
calc R_h =	3.4	5.1	6.9
R_h guessed was	10.0	8.0	6.8

Therefor the resistance was V*/V= 0.303, n=0.07, the mean velocity was 2.03 fps, and the flow depth was 6.8 ft. If the equations for partially submerged flow were used, a depth of 12.1 ft would have been calculated.

19-4 Figure 24 demonstrates the stage discharge that the above example would produce. Figure 24 also shows the variation of predicted resistance with channel velocity. There is a transition that occurs when the effective leaf mass begins to rapidly change with partially submerged flow. With increased velocity and depth for partially submerged flow, resistance increases because of the increase in plant blockage. With increased velocity and depth for submerged flow, a constant blockage, the resistance decreases.

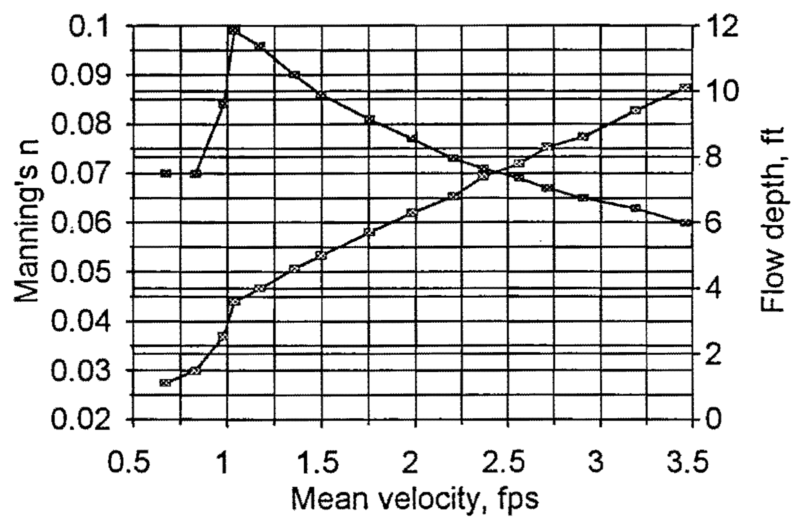


Figure 24 Stage Discharge Plot for Example

19-5 The parameters used with equations 40 through 43, include the variables of velocity and depth. Because of this, any solution of a stage discharge relationship will require an iterative procedure. Table 14 demonstrates an iterative solution with an example of two types of plants with submerged flow. An alternative approach was tried in which the resistance analysis and Equations 40 through 43 were modified by replacing the inertial force $\rho V^2 A$ with the shear stress force τA, and the Reynold's number was replaced by the slope S. Equation 47 was derived for submerged flow and Equation 48 was derived for partially submerged flow.

$$\frac{V^*}{V} = 0.0357 \left(\frac{E\,A_s}{\gamma\,R_h\,S\,A} \right)^{0.174} \left(\frac{H}{Y_O} \right)^{0.288} (MA)^{0.257} \left(\frac{1}{S} \right)^{0.0575} \qquad \textbf{(47)}$$

$$\frac{V^*}{V} = 0.893 \left(\frac{E\,A_s}{\gamma\,R_h\,S\,A} \right)^{0.0833} \left(\frac{A_S}{A} \right)^{0.0921} (MA)^{0.119} \, (S)^{0.267} \qquad \textbf{(48)}$$

Equations 47 and 48 have the advantage that an iterative solution is not required. However, Equations 47 and 48 have a number of severe limitations. They do not work for multiple plant groupings (with errors of over 70%), they are limited to shallow depths just greater than the plant height, they ignore the effect of viscosity and Reynold's number, and they can only be applied where uniform flow exists (the energy slope equals the bed slope). The equations also did not correlate or predict reasonable values for plant drag force.

19-6 Figure 25 demonstrates the characteristic relationship between the modulus of elasticity and the length ratio H/D_S. At the time of this report, there was not enough data available to determine plant characteristic relationships. However, Figure 25 does show that the relationships do exist, and once determined, will greatly aid in the prediction of resistance.

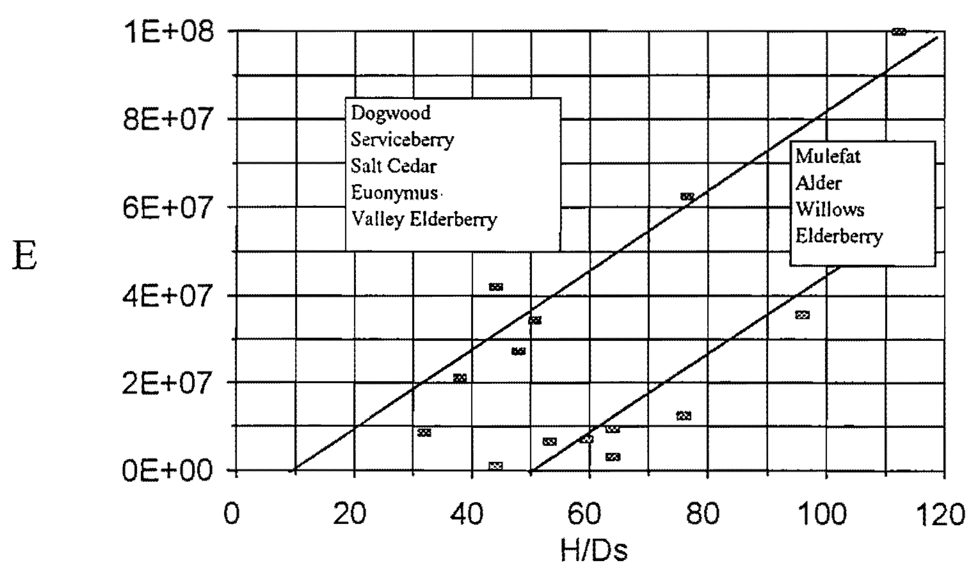


Figure 25 Characteristic Relationship of Plant Elasticity (E) versus Plant H/Ds

Section 20 SUMMARY AND CONCLUSIONS

1. A total of twenty different plants were tested in a large flume and a smaller sectional flume to determine flow resistance and drag force. Over 214 tests were completed at varying velocities, flow depths, plant densities, plant types, and plant dimensions. Five groups of multiple plant types and sizes were tested. Resistance testing included submerged and partially submerged flows. Phase I of testing was completed in 1994 using a clay bed, and Phase II of testing was completed in 1995 using a fixed mortar bed. The test data can be found in Volume 2 of this report, and the summary of test results can be found in Tables 4 through 12, Sections 11 and 12 of Volume 1.

2. Vegetative flow resistance was found to decrease with velocity and depth for submerged plants. Resistance increased with depth for partially submerged plants as the blockage area increased until the plants were submerged. The transition between submerged and partially submerged flow occurred at a depth of about 80% of the undeflected height of the plants. An important observation of the submerged plants was that the plants were flexible and the leaf mass formed a streamlined (teardrop) shape that reduced the flow forces on the plants. The teardrop shape also protected the leaves from being pulled off the plant stems, and reduced breakage of the smaller plant stems. Minimum plant velocity limits of 3 to 4 fps were observed for leaf failure. However, most of the leaf and stem failures were the result of impact with bed material and debris being transported by the high velocities. Figures 9 through 14 demonstrate the distortion of the test plants at different flows.

3. Another important observation during the testing was that the leaf mass or layer of foliage could divert flow beneath the foliage layer (Figure 11). The flow diversion resulted in significant velocities along the channel bottom which caused general scour (Figure 13) and increased sediment transport (Figure 12). Even the clay test bed of Phase I suffered significant erosion at channel velocities of 4 fps. The ground cover plants prevented significant channel bottom velocities, but the plants and exposed bed between plants, experienced local scour from three-dimensional vortices formed from the flow above the plants (Figure 14). It was observed that combinations or groups of different types and sizes of plants produced the lowest bottom velocities and erosion potential.

4. The major premise for the development of equations and methodology for

plant resistance was based on the assumption that resistance can be directly related to the shear stress produced by the drag force of the plants (see Equation 3). A comparison (Figure 23) of the measured drag forces and the measured flow resistance coefficients verified the assumption. Semi-empherical equations were then developed to relate resistance coefficients or drag force to parameters of plant flexibility, flow inertia, ratio of flow depth to plant height, plant density and blockage area, and the Reynold's number (Equation 37). The equations were derived as power relationships. It was found that semi-log relationships, similar to other resistance equations, would not fit the test data. Equations 40 and 41 apply to submerged flows, and Equations 42 and 43 apply to partially submerged flows.

Submerged flow: $Y_O > 0.8(H)$

$$\frac{V^*}{V} = 0.326 \left(\frac{E\,A_s}{\rho\,V^2 A} \right)^{0.128} \left(\frac{H}{Y_O} \right)^{0.187} (MA)^{0.182} \left(\frac{1}{R_E} \right)^{0.0828} \qquad \textbf{(40)}$$

Partially Submerged flow: $Y_O < 0.8(H)$

$$\frac{V^*}{V} = 4.5x10^{-5} \left(\frac{E\,A_S}{\rho\,V^2 A*} \right)^{0.224} (MA*)^{0.0592} \left(R_E \right)^{0.530} \qquad \textbf{(42)}$$

5. Figures 19 through 21 show the correlation of predicted resistance coefficients (from Equations 40 through 43) with the plant resistance coefficients measured in this study. Table 13 shows the application and comparison of predicted resistance with the measured resistance from several field studies. The application of Kouwen and Li's (1980) equations and Masterman and Thorne (1992) methodology for plant resistance was compared with the test results. The correlation of their equations was poor, but it should be noted that their equations apply to tall, dense grasses.

6. The accuracy and suitability of the methodology and equations developed in this study were evaluated on the criteria of whether the parameters and equations could be applied to: (1) both submerged and partially submerged flows; (2) plants with single and multiple stems; (3) plant groupings of different types and sizes of plants; (4) limited field data; and (5) the ability to predict the resulting drag force on a plant. The equations met all of the above criteria with satisfactory results. However, because the variables of velocity

and depth were used in the parameters, an iterative solution is required to solve for flow resistance and depth (or velocity). In an attempt to eliminate the need for an iterative solution, other parameters, such as $(\gamma R_h SA)/(EA_S)$, were evaluated. They were all found to be incompatible with higher flow depths and multiple plant groupings, and produced much larger errors in the fit of data. They also could only be applied to conditions of uniform flow.

7. The resistance coefficients predicted by Equations 40 through 43 represent the combined resistance of the bed and the plants. Resistance coefficients due only to vegetation must be calculated by subtracting the base resistance of the bed from the resistance coefficients predicted from the equations.

8. Equations 40 through 43 were found to work well with multiple plant groupings or groups of different sizes and types of plants. Average plant dimensions and characteristics are used in the equations, and the plant dimensions are determined from a weighted average (by plant number) for the different sizes and types of plants.

9. One of the major plant characteristics, used with the equations is the modulus of elasticity. This parameter could not be eliminated from the equations, and a method was presented for determining elasticity for plants. The characteristic of plant density was defined as the number of plants per unit area. This differed from the definition of other researchers for relative density. The plant density was combined with the plant blockage area to form a dimensionless parameter that represented the combined flow blockage. Blockage area and plant density must be determined differently for plants than for dense grass, since there is significant flow around and through plants. It may be possible to characterize or develop characteristic relationships between variables such as blockage area or modulus of elasticity and the plant height (see Figure 25). Such relationships will greatly aid in predicating resistance.

10. The equations and methodology presented in this study are based on fundamental flow variables and plant characteristics. The equations are semi-empherical in nature and should apply to other types and sizes of plants not tested in this study. Because the equations utilize both flow velocity and depth, the application of the equations require an iterative solution. Table 14 presents an example of determining the resistance and flow depth for a multiple plant grouping.

RECOMMENDATIONS:

1. This study is fairly unique in that actual plants were laboratory tested under conditions as close to field conditions as possible. Although a number of different plants were tested, it is recommended that other types of plants still need to be tested in a prototype large flume environment. The application of drag force data from sectional flume testing and field measurements will probably require the use of the plant approach velocity. More testing is needed with large flumes to develop the methods to predict plant velocities in fully developed channel flows.

2. The equations and methodology of this study can be applied to two-dimensional flow models with consideration for channels with vegetated banks. However, more research is needed to study the prediction of local velocities and plant drag forces so that three-dimensional models can be developed.

3. It is recommended to use the conveyance method to calculate equivalent Manning's n for use with the left and right flood plains of HEC-2. However, Manning's n_b is not constant with flow parameters, and this will complicate the use of programs such as HEC-2. The methodology for using n_b with HEC-2 will have to be developed.

4. More field data is necessary to determine the relationships between plant characteristics and plant height for different types and species of plants. The relationships will simplify the efforts and applications of the resistance equations.

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