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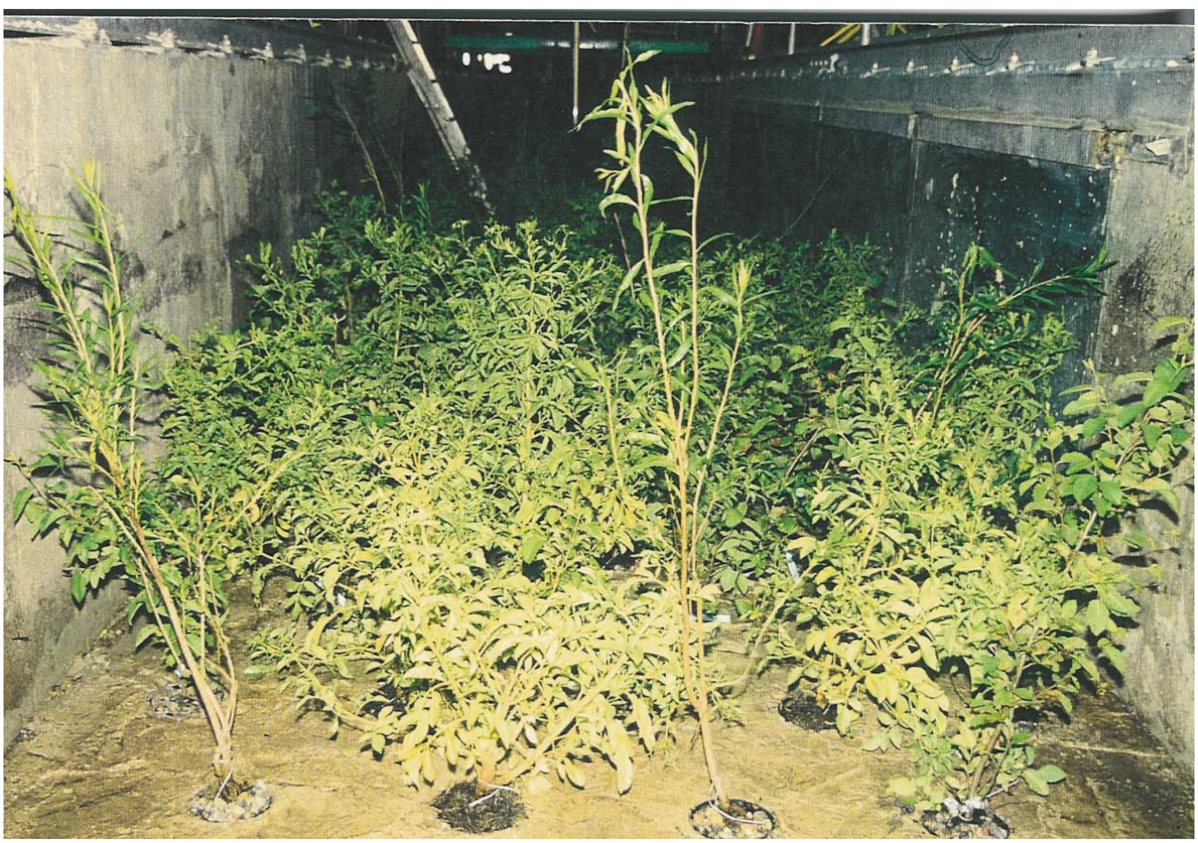
Determination of Resistance Due to Shrubs and Woody Vegetation

Gary E. Freeman, William J. Rahmeyer, and Ronald R. Copeland

October 2000



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Determination of Resistance Due to Shrubs and Woody Vegetation

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Preface

The investigation reported herein was conducted by and for the U.S. Army Engineer Research and Development Center. The majority of the research was funded under Contract DACW39-94-K-0009 and conducted by the Utah Water Research Laboratory. A smaller portion of the research was funded under DACW39-97-M-1413 consisting of field investigations of plant stiffness and conducted by Dengari, Inc. Field measurements of hydraulic losses under actual high-water conditions and subsequent determinations of plant stiffness were conducted by Dr. Gary Freeman, former research hydraulic engineer, ERDC. All research reported herein was funded by the ERDC, Vicksburg, MS, as a part of the Flood Control Channels and Flood Damage Reduction Research Programs. Dr. Ronald R. Copeland, ERDC, supervised this research.

Research at the Utah Water Research Laboratory was conducted by and under the supervision of Dr. William Rahmeyer with the assistance of Mr. David Werth and other graduate research assistants. Dr. Gary Freeman conducted the research for Dengari, Inc. The authors of this technical report were Drs. Gary Freeman, William Rahmeyer, and Ronald Copeland.

The studies reported herein have been conducted over the period from 1993 to 1998 and were under the general supervision of Mr. F.A. Herrmann, Director of the Hydraulics Laboratory, Dr. J. R. Houston, former Director of the Coastal and Hydraulics Laboratory, Mr. M. B. Boyd, Dr. L. Daggett, Dr. W. H. McAnally, Jr., and Dr. P. G. Combs, Division Chiefs. The work was performed initially under the supervision of Mr. William A. Thomas with supervision subsequently transferred to Dr. Ronald R. Copeland, Research Hydraulic Engineers. Mr. D. L. Derrick, Research Hydraulic Engineer, was also involved in the supervision of contracts, research coordination, and field research efforts.

At the time of publication of this report, Dr. James R. Houston was Director of ERDC, and COL James S. Weller, EN, was Commander.

List of Variables

Numerous variables are used throughout this report. These variables are listed here for convenience. Figures 1 and 2 show the measurements that define the variables involving the leaf mass and plant dimensions for submerged and emergent (unsubmerged or partially submerged) flow conditions.

The variables are defined as follows:

A	Cross sectional flow area, ft^2 or m^2
Ai	Frontal area of an individual plant blocking flow, approximated by the equivalent rectangular area of blockage H’ by We, ft^2 or m^2
*Ai**	Net submerged frontal area of a partially submerged plant, ft^2 or m^2
As	Total cross-sectional area of all of the stem(s) of an individual plant, measured at H/4, ft^2 or m^2
b	width of channel flume, ft or m
C	Chezy resistance coefficient, ft½/s or m ½/s
CD	Drag coefficient of vegetation, dimensionless
Ds	Stem diameter, measured at a height of H/4, ft or m
Es	Modulus of plant stiffness, lbf/ft^2 or N/m^2
f	Darcy-Weisbach friction factor, dimensionless
fb	friction factor for the bed and plants, dimensionless
fw	friction factor for the walls, dimensionless
*F*45	The horizontal force necessary to bend a plant stem 45 deg, lbf or N
FD	Drag force, lbf or N
Fr	Froude number, dimensionless

g	Acceleration due to gravity = 32.17 ft/s^2 or 9.806 m/s^2
H	Average undeflected plant height, ft or m
H'	Undeflected height of the leaf mass of a plant, ft or m
H^*	Undeflected height of leaf mass that is below water surface for a partially submerged plant, ft or m (See Figure 2)
I	Second moment of inertia of cross section of plant stem, ft^4 or m^4
K_n	Units conversion factor for Manning's equation, 1.4861 ft$^{1/3}$/s or 1.0 m$^{1/3}$/s
L	Channel reach length, ft or m
M	Relative plant density, number of plants per ft^2 or m^2
n	Total Manning's roughness coefficient, including sidewall roughness
n_b	Manning's resistance coefficient for vegetation and channel bed
n_{veg}	Manning's resistance coefficient for vegetation
n_o	Manning's resistance coefficient for the bed
P	Wetted perimeter, ft or m
R_e	Reynolds number, $R_e = V R_h / \nu$
R_h	Hydraulic radius, R_h = flow area / wetted perimeter, ft or m
R_b	Hydraulic radius for the bed and plants, ft or m
R_w	Hydraulic radius for the walls, ft or m
S	Bed or energy slope, dimensionless
S_o	Bed slope , dimensionless
S_f	Energy slope, dimensionless
V	Mean channel velocity, ft/s or m/s
V_P	Local plant approach velocity in front of the leaf mass, ft/s or m/s
V_*	Shear velocity, $V_* = (g R_h S)^{1/2}$, ft/s or m/s
V_*/V	Resistance coefficient, dimensionless

Y_o	Flow depth, ft or m
W_e	Equivalent average plant width, $W_e = A_i / H'$, ft or m dy/dx Unit change in slope of the water surface
γ	Specific weight of water, lbf/ft^3 or N/m^3
ν	Fluid dynamic viscosity, ft^2/s or m^2/s
ρ	Fluid density, $slugs/ft^3$ (lbf-sec/ft) or kg/m^3
τo	Shear stress on channel bottom, ($\tau o = \gamma$ Rh S), lbf/ft^2 or N/m^2

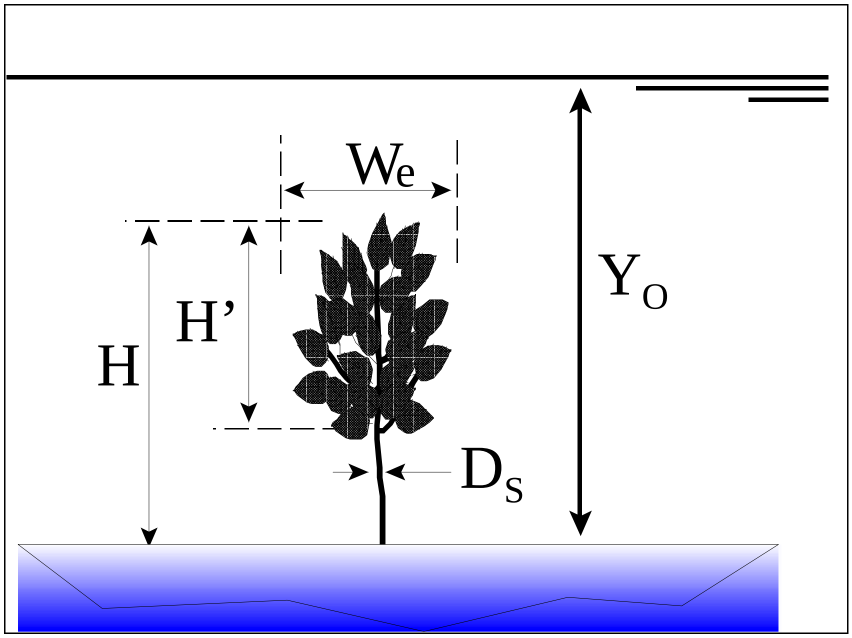

Figure 1. Plant dimension definitions for submerged plants

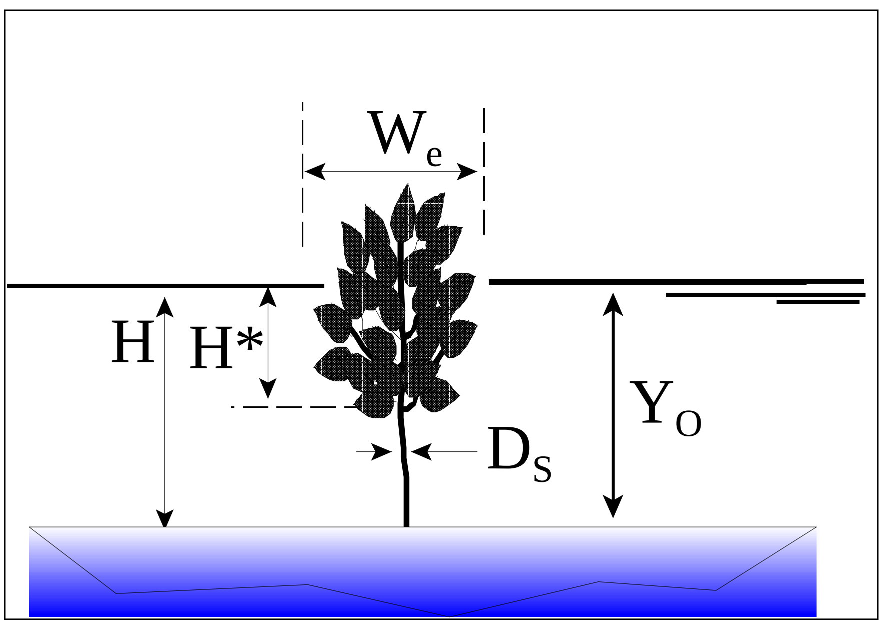

Figure 2. Plant dimension definitions for partially submerged plants

1 Introduction

Background

An important consideration for determining the stage-discharge relationship in rivers and streams is the effect or influence of vegetation on the overall head loss along a channel and in the overbank. Plants in the floodplain and along the banks can increase or even decrease the effective flow resistance. The vegetation may be natural or it may have been planted to improve aesthetics or habitat, to prevent erosion, or for other reasons.

The impetus for this study came as a result of numerous inquiries from U.S. Army Corps of Engineer District offices regarding the proper hydraulic roughness values to use for shrubs and other aesthetically and environmentally desirable plants. The District offices were involved in the evaluation of vegetative impacts on proposed and existing channels to determine flow capacity and water surface elevations. Given the near complete lack of hydraulic roughness values for shrubs and similar vegetation, the accurate estimation of channel capacity and water surface elevations was difficult at best. The work described herein was carried out under the Flood Control Channels and Flood Damage Reduction Research Programs starting in 1993 and completed in 1997. It was a direct result of District requests for research through the Flood Control Channels Field Review Group

Previous research has been conducted on vegetation such as grasses, agricultural crops, and on the rigid blockage of cylindrical tree trunks. However, little had been studied on the resistance effects of plants and shrubs that are either submerged or partially submerged by turbulent flows. The flexible stems and varying shapes of plant leaf mass greatly complicate the understanding of this resistance. The deformation of plant shape with flow precludes the use of a constant blockage area or the density of plant frontal area in predicting resistance.

The purpose of this study was to investigate the effect of vegetation, particularly ground cover plants, small trees, and shrubs, on flow resistance. Hydraulic losses and drag due to actual plants were measured at the Utah Water Research Laboratory utilizing a large wide flume and a smaller sectional flume.

Research in the flume resulted in the collection of data from more than 220 experiments with 20 different plant species. Experiments were conducted with both homogeneous and mixed plant groupings. Single-stem and multiple-stem plants were included in the plant types evaluated. Plants with and without leaves were evaluated. Plant density, spacing, and size were varied in the experiments. Plants were evaluated over a range of velocities and depths.

A methodology was developed from the laboratory data to predict head loss and resistance coefficients as a function of slope and depth. Input data for the methodology can be collected from the field or estimated plant characteristics may be used.

Resistance Coefficients

Resistance to flow is typically characterized by a roughness coefficient. The most commonly used equation for flow resistance is the Manning's equation:

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

where

V = mean velocity of flow

R_h = hydraulic radius

S = slope of the energy grade

n = Manning's resistance coefficient

K_n = unit correction factor of 1.0 for SI units and 1.486 for non-SI units

Although Manning's equation is used extensively for calculating flow resistance, Manning himself did not recommend it for use, because his research found that n was not constant but varied with velocity and depth.

The ratio of shear velocity to mean velocity, V_*/V, is another form of resistance coefficient. Keulegan (1938) used it to calculate average velocity based on the theoretical vertical velocity profile. The ratio of shear velocity to average velocity may be thought of as the ratio of shear stress to inertial force as indicated in Equation 2.

$$\frac{V_*}{V} = \frac{\sqrt{gR_hS}}{V} = \left(\frac{\tau_o}{\rho V^2}\right)^{1/2} \tag{2}$$

V_* is the shear velocity, g is the acceleration due to gravity, τ_o is the shear stress, and ρ is the density of water.

There are other resistance coefficients in use including the Darcy-Weisbach friction factor, f, and the Chezy C. These can be converted easily to Manning's n as shown in Equation 3.

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

Note that the Chezy coefficient is not dimensionless, and will vary with units. The Manning coefficient is dimensionless only in the sense that K_n will make it dimensionless when units of feet or meters are used in Equation 3.

In this study, resistance equations were developed for the shear velocity to average velocity ratio because it is dimensionless and has a sound theoretical basis, and for the Manning's coefficient because its use is widespread.

The Manning's resistance coefficient for vegetation is calculated in conformity with the Cowan (1956) method for additive resistance. This method consists of additions to roughness for various surface irregularities and vegetation. The equation that describes the method is:

$$n = (n_o + n_1 + n_2 + n_3 + n_4)m \tag{4}$$

where n_o is the base value for a straight, uniform, smooth channel in natural materials; n_1 is an additive value to account for surface irregularities; n_2 is added to account for variations in the channel geometry along the reach; n_3 is an additive value to account for obstructions; n_4 accounts for vegetation; and m is a correction factor for meandering or sinuosity of the channel. The n_4 coefficient used in Cowan's method is based on the net effect of vegetation.

Many published values of Manning's roughness coefficients related to vegetated surfaces include the base resistance, n_0, as a part of the reported vegetation resistance. This is the convention followed in this report. Thus, roughness coefficients reported herein include the effects of both the bed and the vegetation. In Cowan notion this would be expressed as $n = n_0 + n_4$.

The resistance values can be composited into channel averages using several methods. One of the methods is Lotter's 1933 method shown in Equation 5. The Lotter method, presented by Chow (1959), uses vertical bisecting lines to subdivide the channel cross section into subareas for the calculation of flow. This method assumes that the total flow is the sum of the flows in the separate subareas. The equivalent resistance thus developed accounts for the variability in resistance across the channel.

$$n = \frac{PR_h^{5/3}}{\sum_{i=1}^{N}\left(\frac{P_i R_{hi}^{5/3}}{n_i}\right)} \tag{5}$$

P is the wetted perimeter. N is the number of i subsections.

Substitution of Equation 5 into Equation 3 yields a dimensionless compositing equation for V_*/V given in Equation 6.

$$\frac{V_*}{V} = \frac{P R_h^{3/2}}{\sum_{i=1}^{N} \left(\frac{P_i \, R_{h\,i}^{3/2}}{\left(V_*/V \right)_i} \right)} \qquad (6)$$

Resistance Equation for Large Woody Vegetation

Usually, vegetation on the flood plains is larger than that found in the main channel. This vegetation has a major influence on flow depth and resistance during overbank flooding. Petryk and Bosmajian (1975) proposed a method to calculate flow resistance based on the drag forces created by the larger plants and trees that constitute much of the resistance on the flood plains. They derived Equation 7 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.

$$n = n_o \sqrt{1.0 + \left(\frac{C_D \sum A_i}{2g \, A L} \right) \left(\frac{K_n}{n_o} \right)^2 \left(\frac{A}{P} \right)^{4/3}} \qquad (7)$$

Here C_D is the effective drag coefficient for the vegetation in the direction of the flow, A is the cross-sectional area of the flow, in ft^2, ΣA_i is the total frontal area of vegetation blocking the flow in the reach, in ft^2, L is the length of the channel reach being considered, in ft. The expression $C_D \Sigma A_i/(AL)$ represents the vegetation blockage, or the density of vegetation in the floodplain. This expression must be either directly or indirectly measured. The total boundary roughness, n_o, excludes the additive resistance, n_4, for other types of vegetation such as shrubs.

There are several limitations to using Petryk and Bosmajian's equation. The channel velocity must be small enough to prevent bending or distortion of the vegetation, and large variations in velocity cannot 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, according to Petryk and Bosmajian, the flow depth must be less than or equal to the maximum vegetation height. During flooding, the velocities over the floodplains can be relatively high and large degrees of bending and distortion of vegetation often occur. Vegetation types and densities can also vary widely across a floodplain, and water depths often submerge vegetation. However, when tree trunks dominate sections of a floodplain, this method can be used to predict the total resistance coefficient, n.

2 Laboratory Setup and Procedures

Experimental Plants

Two flumes at the Utah Water Research Laboratory were used for laboratory experiments during this study. The large flume (Figure 3), 2.44 m (8 ft) wide by 1.82 m (6 ft) deep by 152.4 m (500 ft) long, was used to measure in situ flow resistance and drag force for groups of uniform sized plants and groups of mixed plants with varying plant density, sizes, and shapes. A sectional flume, 0.91 m (3 ft) wide by 0.91 m (3 ft) deep, was used to measure drag force of individual plants. Thirteen different plant types were evaluated in the large laboratory flume and 10 plant types in the sectional flume. Six combinations of plants typical of different ecosystems were also studied in the large flume. In total, 21 different plant types were evaluated in the two flumes. The plants and their characteristics are listed in Table 1. Field measurements of plant stiffness (Freeman 1997) for four plant types are also listed in Table 1. All plants evaluated were broadleaf deciduous vegetation commonly found in floodplain and riparian zones.

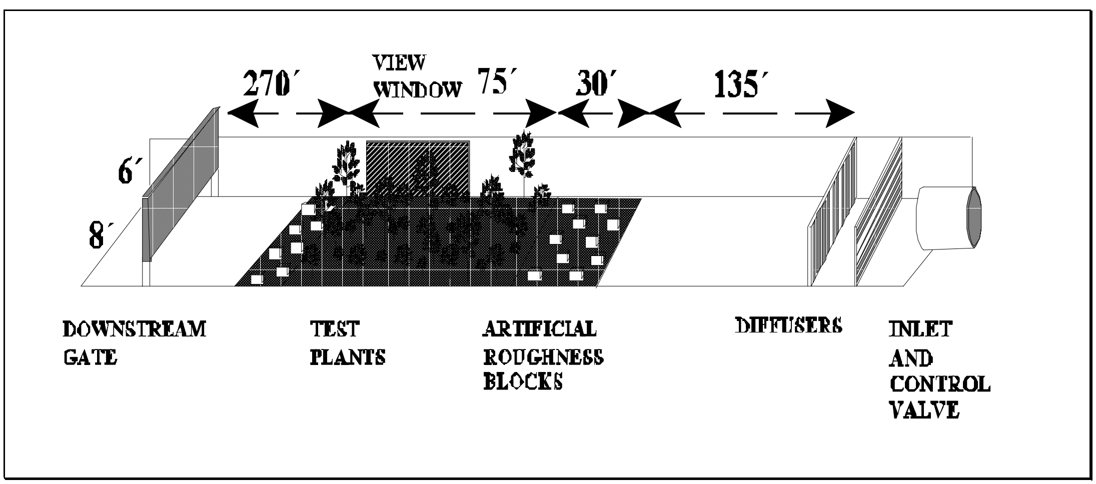

Figure 3. Layout of large flume for plant roughness experiments (To convert feet to meters, multiply by 0.3048)

The plants evaluated in the large flume were placed in staggered rows along the 22.9-m (75-ft) length of the experimentation section (Figure 3). The spacing selected for the plants was based on typical plant spacing found in floodplains. The plant density, M, was calculated as the number of plants per unit area. The plants evaluated in the small flume were placed in a single row of four to five plants along the center line of the flume. A single plant was instrumented for measuring drag force in both flumes. The instrumented plant in the larger flume was located in the center of the 22.9-m (75 ft) by 2.44-m (8-ft) experimentation section. The plant selected for measurement in the small flume was the downstream plant, with four plants located upstream. The experimental setup for the small flume allowed for a more accurate measurement of plant approach velocity (V_P) and drag force (F_D). Roots had to be removed from all the plants used in the small flume, but only the plant used to measure drag force in the large flume required root removal. All other plants in the large flume were placed intact, with root structure and original soil, into a 20.3-cm (8-in) deep experimental bed.

The range of variables measured in the large flume were:

a. Flow depths from 0.4 to 1.4 m (1.3 to 4.7 ft).

b. Average flow velocities from 0.15 to 1.1 m/s (0.5 to 3.6 ft/s).

c. Measured resistance V_*/V from 0.13 to 0.45 and n from 0.04 to 0.14.

d. Plant heights from 0.20 to 1.52 m (0.66 to 5 ft).

e. Plant widths from 0.076 to 0.91 m (0.25 to 3 ft).

f. Plant densities from 0.53 to 13 plants / m^2 (0.05 to 1.2 plants / ft^2).

g. Plant modulus of stiffness from 5.3×10^7 to 4.8×10^9 N/m^2 (1.1×10^6 to 1.0×10^8 lbf/ ft^2).

h. Reynolds numbers from 1.4×10^5 to 1.6×10^6.

Large Flume Experimental Setup

The large flume experimentation section had a bed that would accept plants with their root systems intact. In the first phase of the study, the bed consisted of a layer of gravel, to assist in drainage, covered with a cap of compacted clay. This material supported the plants and was intended to prevent them from washing downstream. In the second phase of the study, the compacted clay was replaced with a gravel bed and a mortar cap. The mortar cap greatly facilitated the changing of plants and experimental setups. The mortar cap had 158 3.8-L (1-gal) plant containers in the bed in staggered rows of four and five plants per row. When particular containers were not in use they were capped flush with the top of the mortar cap to prevent the introduction of additional roughness.

Upstream and downstream of the experimentation section the flume contained a section of roughened bed. The roughness elements consisted of cinder blocks that were adjusted until they produced a fully-developed turbulent velocity distribution upstream and downstream of the experimentation section.

At the beginning of each experiment, at the downstream end of the clay or mortar bed, stop logs were inserted to allow for slow filling of the flume. This was done to protect plants during filling. As discharge was slowly increased to the desired level, stop logs were removed. Some stop logs remained during the experiment to maintain a constant velocity profile throughout the experimentation section. At the downstream end of the flume, 91.4 m (300 ft) downstream of the experimental section, a hydraulic gate was used to control flow depth.

Water from the river adjacent to the laboratory entered the flume from a 122-cm (48-in) pipe 50.3 m (165 ft) upstream from the experimentation section. Water temperature was measured and found to be 10°C (50°F) for all experiments. A remote controlled butterfly valve in the 122-cm (48-in) pipeline was used to control the flow of water into the flume. A Mapco sonic meter was used to measure the flow rate in the inlet pipe. Downstream from the inlet pipe, jet flow was dissipated using a series of vertical and horizontal distribution vanes.

A wheeled platform that moved on tracks adjacent to the flume sides was used to take depth and velocity measurements. This platform was positioned at 1.52-m (5-ft) intervals along the length of the experimental section to facilitate measurements. Water-surface elevations were measured with the help of a stationary transit and a measuring rod along the center line of the flume. Flow velocities were taken with a Marsh McBirney Model 201 portable water current meter.

A single plant centered horizontally in the flume was selected to measure drag force. An average-sized plant was selected and inserted into a platform. The platform was a shallow metal box with ball bearings in the bottom and a metal plate resting upon the ball bearings as shown in Figure 4. The instrumented plant, with its roots removed, was attached to the plate. A Vishay Instrument Model P-350 strain indicator was then attached to the downstream end of the plate to measure the drag force applied to the plant by the moving water column. This drag force was measured as a compression force. During the experiment 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 also covered with a plastic lid to reduce friction drag on the platform. The strain gage was zeroed at the start of each series of experiments. The range of the strain gage was 0 to 44.5 N (10 lbf). The sensitivity of the strain gage was 45 micro-cm per cm per N (200 micro-inches per inch per pound). Measurements were taken to the nearest 2.5 micro-cm (1.0 micro-inch.)

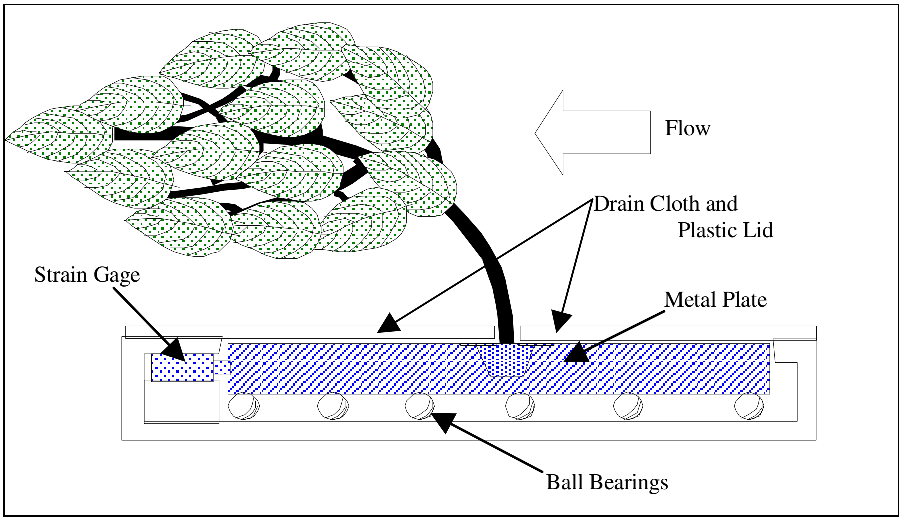

Figure 4. Experimental setup to measure plant drag

Large Flume Operating Procedures

Measurements were made of plant dimensions and plant characteristics before each series of experiments. Plant height and width, leaf size, and stem height were measured. The number of branches and stems were counted. The diameter of stems and branches was recorded, and bending characteristics were measured. The forces required to bend the plant 45 deg and horizontal at different heights along the stem were determined. A strain gage was first attached to the top of the plant. After the bending forces and deflection were determined there, the gage was hooked to the center of the plant and the bending forces were again measured.

During the first phase of the study, prior to beginning each series of experiments, the bed was leveled and a layer of topsoil placed and compacted on top of the clay bed. The mortar cap used in second phase of the study did not require maintenance and leveling for each series of runs. The plants were placed in the flume just prior to the experiment and 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 was zeroed. Flow and depth were controlled with the downstream gate and the 122-cm (48-in) inlet butterfly valve. Time was allowed for the flume to reach equilibrium before measurements were taken for each run.

Typically, nine runs were made for each series of experiments. 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 plants were usually submerged, even at low depths, because the flow forces were adequate to bend the plants with the flow. Some runs were conducted near the end of the study with the larger plants partially submerged, to aid in determining a relationship for partially submerged plants.

Water-surface elevation was measured at 1.52-m (5-ft) intervals along the length of the flume's experimentation section. At the midpoint of the experimental section, velocity measurements were taken at different depths to establish a vertical velocity profile. Velocity measurements were also taken at the center of the leaf mass just upstream of the plant used to measure drag force. The plant approach velocity was measured 5.1 cm (2 in) upstream of the instrumented plant to avoid making a measurement in what could have been a stagnation region at the upstream face of the plant. It was determined early in the study that velocity measurements taken in the plant mass and at the upstream face of the plant were inconsistent because of the interference of individual leaves, but the velocity measurements did show that there was still substantial velocity and flow through the plant mass. Drag force was determined from the strain gage measurements for many, but not all, experimental runs. As the depths and velocities were varied, the plants and bed (for Phase I) were observed through the view window to document soil movement, plant distortion, and plant failure.

Small Sectional Flume Setup

A smaller sectional flume was used to study the drag forces developed on single plants. Water was supplied by a 0.914-m- (3-ft-) wide by 0.914-m- (3-ft-) high channel running perpendicular to the flume entrance. A baffle was placed at the entrance of the flume to straighten the incoming flow and a Plexiglas observation window was installed in the side of the flume.

Since the bottom of the flume consisted of smooth steel, it was necessary to devise a method to secure the plants in the flume. A 3.81-cm- (1½-in.-) thick false deck was constructed of smooth, painted plywood. The deck was bolted through the bottom of the flume and sealed with silicon caulk. Several 2.54-cm (1.0-in) holes were drilled through the plywood to the steel bottom. These holes were designed to hold plants in a layout that would create a flow regime around the plant similar to the flow regime of the plant in the large flume.

To attach the plants to the flume bottom, a beveled rubber grommet and wide-flanged washers were used. The roots of the plants were cut off at the base of the stem, and the plant stem inserted through the washer into the grommet. The rubber grommet was used to protect the base of the stem and prevent breakage of the stem. Without the grommet, the plant tended to break where the stem contacted the surface of the plywood floor when the plants were subjected to high velocities. The rubber in the grommet would give slightly, however, 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 that allowed the grommet to be attached to the plywood floor with screws. The beveled grommet was slightly larger than the holes and when the screws were tightened, the washer compressed the grommet into the hole, securing the plant to the floor of the flume.

The instrumented plant in the small flume also had a grommet, but was attached to a smooth aluminum plate rather than the plywood floor. The plate was 15.2-cm (6-in) wide by 30.5-cm (12-in) long and 2.54-cm (1-in) thick. The plate provided a platform by which to measure the drag force produced on the plant. A hole was drilled in the plate and a shorter grommet was used because the plate was not as thick as the false deck. The plant was inserted through the washer and the grommet screwed to the plate in the same method as with the other plants.

To allow placement of the plate into the flume floor, a 16.5-cm (6-½ in.) by 31.8 cm (12-½ in.) rectangle was cut in the center of the floor along the center line of the flume. Since the floor was 3.81-cm (1-½ in.) thick, 1.27-cm- (½-in.-) diam 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. It also raised the top of the plate to a height of 3.81 cm (1-½ in.), 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.

The same strain gage used in the large flume experiments was used in the small flume. It was placed and centered directly behind the aluminum plate to measure the drag force as compression. The gage and connections were sealed in waterproof bags. The strain gage was temperature compensating and always zeroed in place and underwater. The calibration of the gage was checked before each series of experiments.

Elastic bands or springs were attached to both the plate and the plywood floor immediately downstream and to the sides of the plate. This held the plate firmly in contact with the strain gage and centered in the floor cavity.

Velocity measurements were made using a propeller type Ott velocity meter. Velocity measurements were taken at the center of the leaf mass just upstream of the instrumented plant.

Small Sectional Flume Operating Procedures

Measurements were made of plant dimensions and plant characteristics before each series of experiments. Plant height and width, leaf size, and stem height were measured. The number of branches, stems, and leaves were counted. The diameter of stems and branches was recorded, and bending characteristics were measured.

The roots of the plants were then removed and attached to either the plywood floor or the aluminum plate. Stop logs were placed to a height of 0.914-m (3 ft) at the downstream end of the flume. This allowed the flume to be completely filled and the strain gage set to 0 to compensate for any buoyancy effects.

Each plant was subjected to a series of 10 runs. Each run was at an increasing velocity, ranging from approximately 0.076 to 2.43 m/sec (0.25 to 8 ft/sec.) During each run, the velocity directly upstream of the plant and the compression on the strain gage were recorded. This velocity was taken at the center line 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 vertical center line of the leaf mass. The angle the plant deflected was determined from marks drawn on the sidewalls of the flume. Videotapes were taken to allow for more detailed observation of the plants at a later time.

After the plant was subjected to 10 different velocities, all leaves were removed. The plant was then immediately subjected to 10 more runs. Velocity, drag, and deflection data were again recorded as previously described.

3 Results and Analysis

Resistance Coefficients from Head Loss Measurements

Twenty-one different series of experiments were completed in the large flume using different plant types, plant combinations, plant heights, plant spacings, flow velocities, and depths. Plant characteristics are listed in Tables 1 and 2 in SI and non-SI units, respectively. The runs were videotaped as well as photographed. One run was made to determine the bed roughness of the flume without plants on each bed type (clay and mortar).

Tables 3 and 4 present results from the large-flume homogeneous-plant-grouping experiments in SI and non-SI units, respectively. Tables 5 and 6 present the results from large-flume mixed-plant-grouping experiments in SI and non-SI units, respectively. Water-surface elevation, average depth, and discharge were measured. Average velocity was determined from the continuity equation. The average roughness coefficient came from an iterative solution of the backwater equation in which calculated water-surface elevations were matched to measured water-surface elevations. In the backwater equation, Equation 1 was used to determine n and Equation 2 to determine V_*/V. Average energy slope is presented in Tables 3-6. Flume wall effects were accounted for by the method advanced by Vanoni and Brooks (1957).

A typical velocity profile measurement is shown in Figure 5. The profile demonstrates the effect of leaf mass on velocity. The plant approach velocity is the velocity that occurred upstream at the center line of the leaf mass of the plant. The velocity significantly increased below the leaf mass. Velocity profile measurements are reported in Rahmeyer et al. 1996.

Average channel velocities between 0.914 and 1.22 m/s (3 and 4 ft/sec) were necessary to cause either the leaves to break off the plants or for the stems to break. These velocities also caused significant movement of bed material in the Phase I experiments. It is possible that many of the leaf and stem failures may have been due to the impact from large bed material, i.e., gravel size particles, being transported by the flow.

Another observation was that shrubs with open areas beneath the primary leaf mass were diverting significant amounts of flow beneath the leaf mass. In

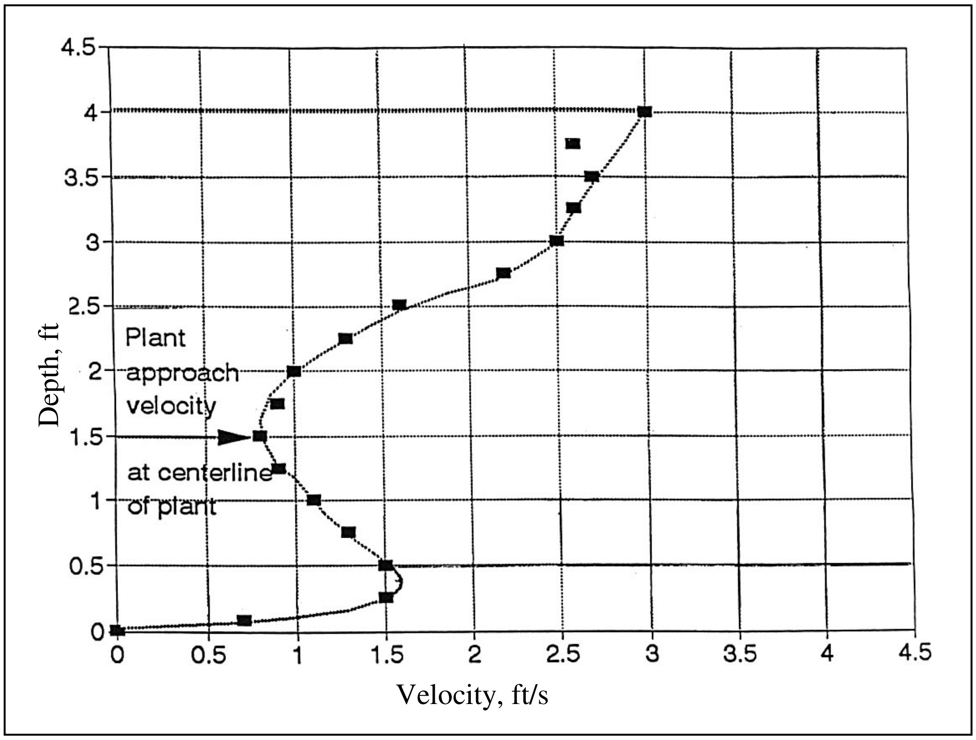

Figure 5. Example velocity profile for an experimental run with dogwoods (To convert feet to meters, multiply by 0.3048)

some cases velocities below the leaf mass approached surface velocities and were sufficient to transport even the largest size gravel particles.

The *Euonymus* plants were ground cover plants with leaves extending to the bed. These plants, when used in a typical spacing, left areas of the bed exposed to flow. Measurable scour was noted in these areas for all Phase I experiments. The *Euonymus* plant experiments were stopped when scour began to wash the plants away. Only the wire attached to the plant stems kept the plants from being washed downstream. It was observed that local scour was occurring from three-dimensional vortices that appeared to be similar to those typically associated with scour around bridge piers.

Figures 6-11 demonstrate the effect of velocity on plant deformation, sediment transport, and scour.

Calculation of Roughness Coefficients

The hydraulic roughness and the Manning's coefficient n for plant resistance were calculated by using an initial estimate of a total Manning's roughness coefficient and then adjusting the n value to best fit the gradually varied backwater curve of measured water-surface elevations along the experimental section. Equation 8 was the equation used to fit the backwater curve.

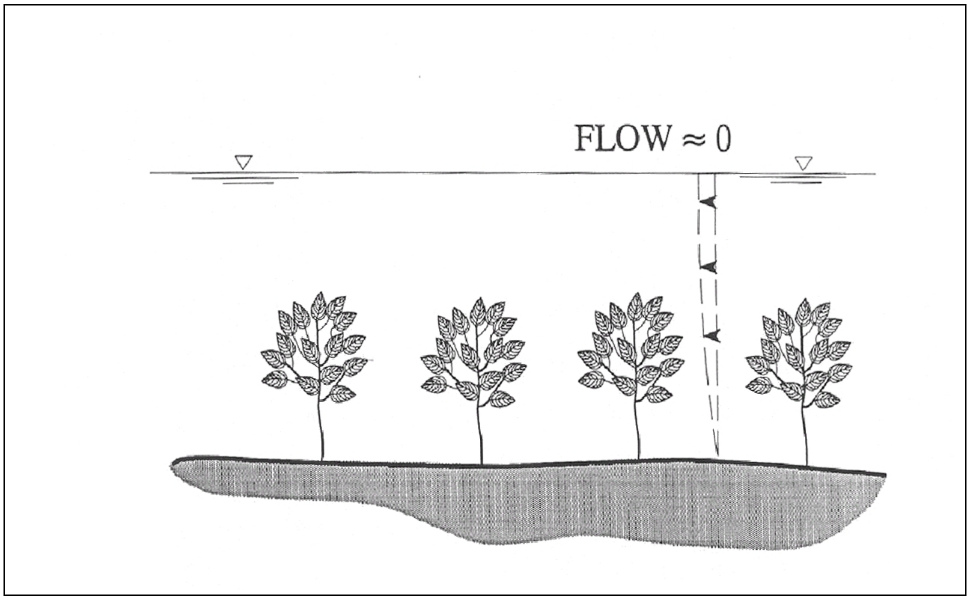

Figure 6. Plants at zero flow

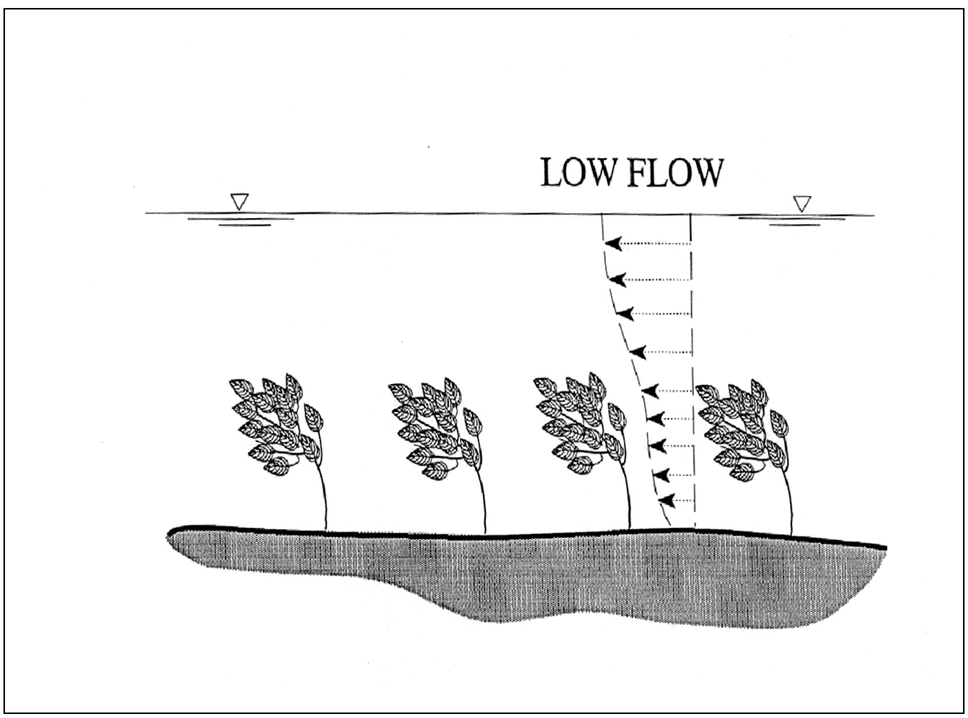

Figure 7. Plants at low flow

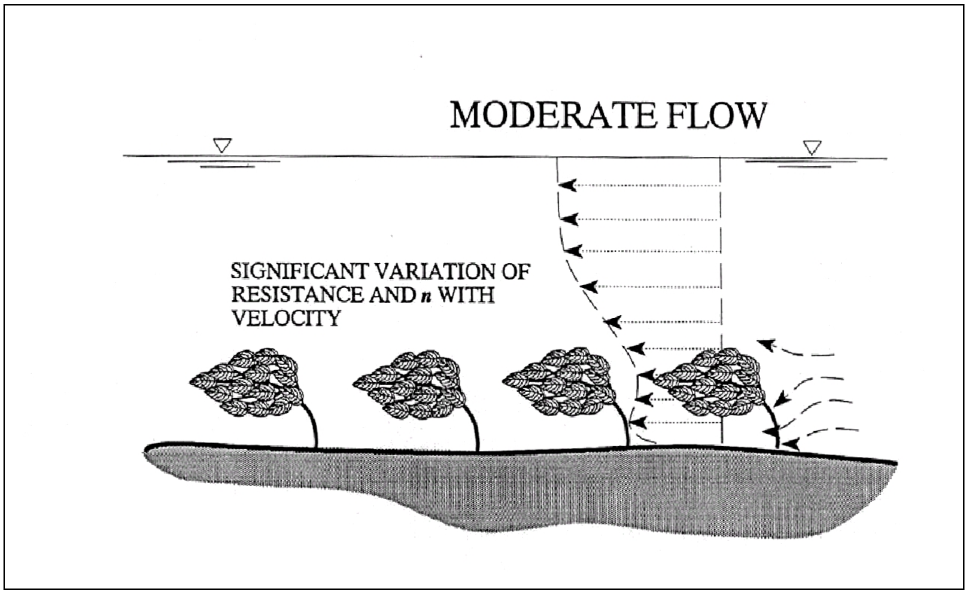

Figure 8. Plants at moderate flow

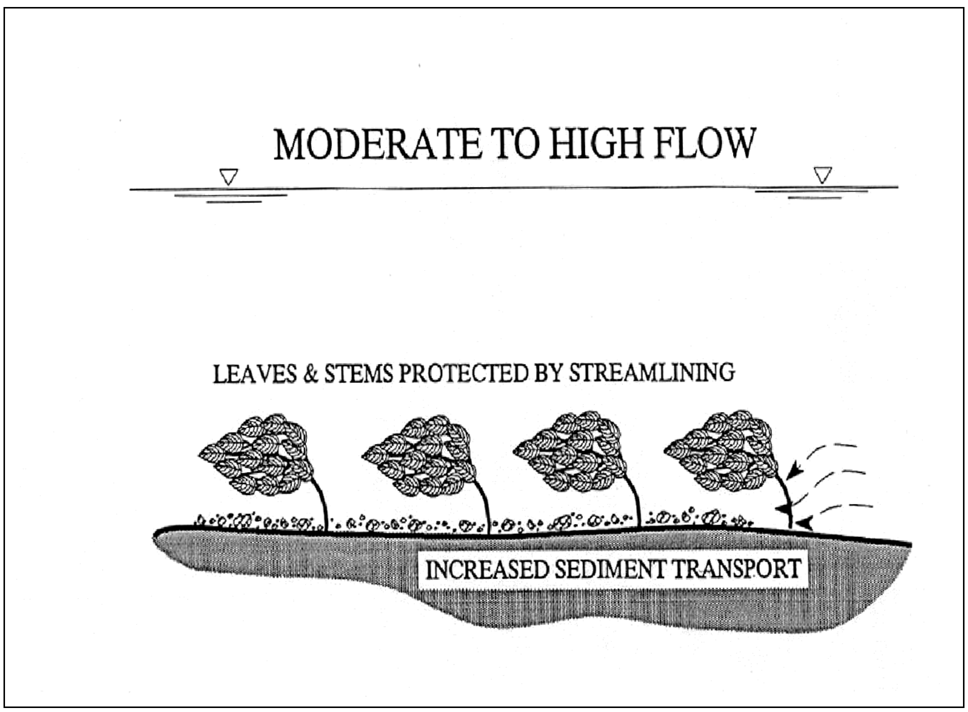

Figure 9. Plants with sediment transport

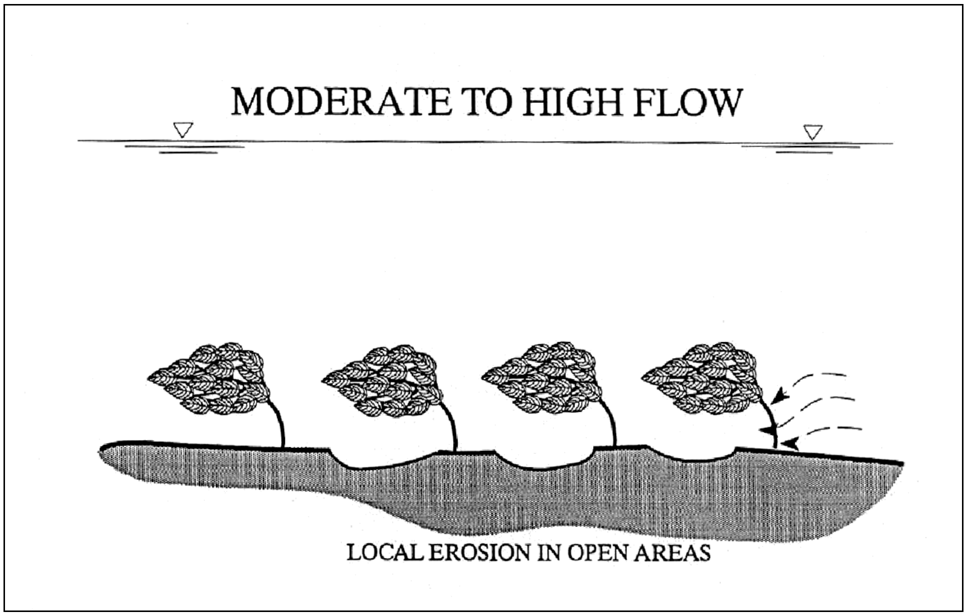

Figure 10. Plants with local erosion

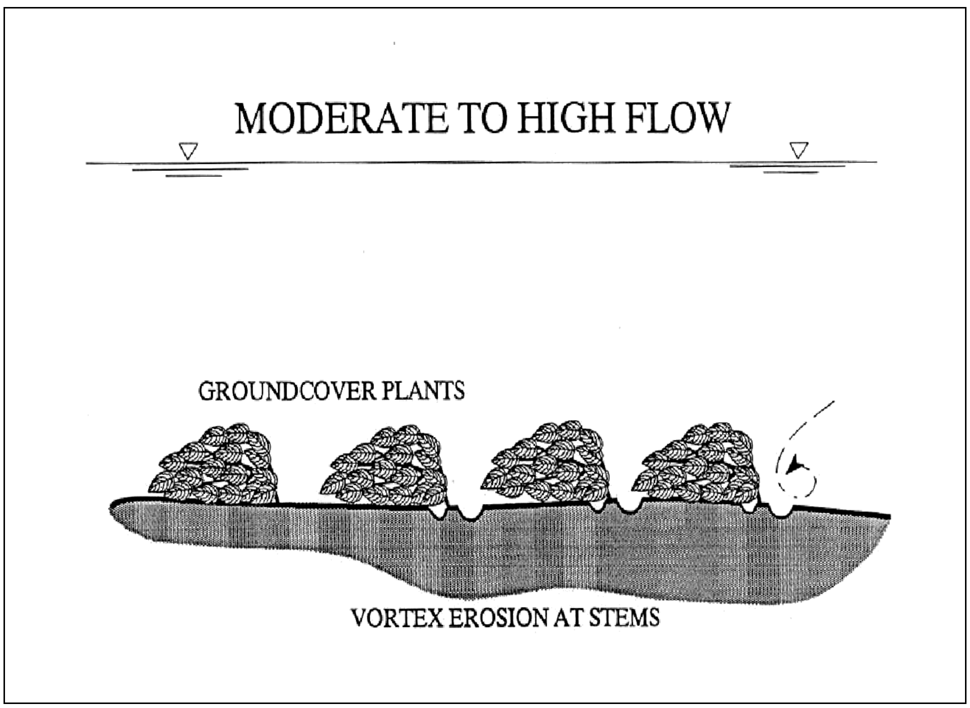

Figure 11. Plants with stem erosion

$$\frac{dy}{dx} = \left(\frac{S_0 - S_f}{1.0 - F_r^2} \right) \qquad (8)$$

Here 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) using the estimate of Manning's n, the mean velocity, V, calculated from the continuity equation, and the hydraulic radius, R_h. The Froude number was calculated from Equation 9.

$$F_r = \frac{V}{\sqrt{g\ R_h}} \qquad (9)$$

The Manning's n for the vegetation and the bed was then iteratively solved using a trial and error process until the shape of the backwater curve predicted by Equation 8 was the same as the measured curve of the actual water surface. Figure 12 is an example of the backwater curve fit for a run with a total Manning's n of 0.062.

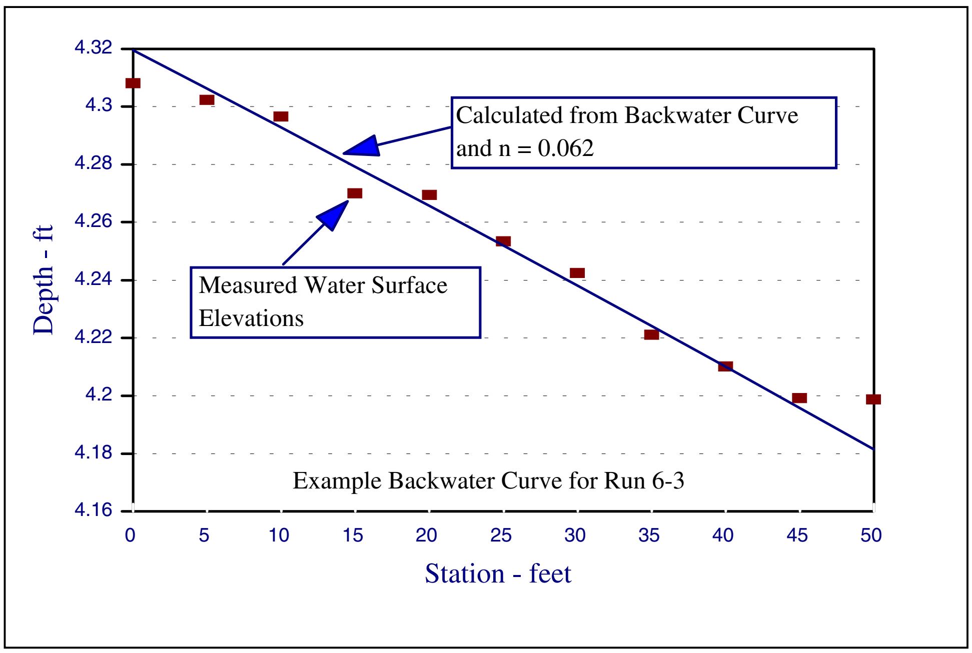

Figure 12. Typical backwater curve for experimental runs (To convert feet to meters, multiply by 0.3048)

From the total Manning's n the value of n_b, the bed and plant roughness, was determined. The first step in this determination was to convert the total n to a Darcy-Weisbach friction factor, *f*, by Equation 10.

$$\sqrt{f} \quad = \quad \frac{n\sqrt{8\,g}}{K_n \; R_h^{1/6}} \tag{10}$$

The coefficient of friction for the bed and plants, f_b, was determined using a correction for flume wall effects. The coefficient of friction for the walls, f_w, was determined from Equation 11. This equation was regressed for this study to fit the correction figure presented by Vanoni and Brooks (1957).

$$f_w \quad = \quad 0.274367\left(\frac{R_e}{f}\right)^{-0.175092} \tag{11}$$

R_e is the Reynolds number. Equation 11 was a power fit regression with an R^2 of 99.98 percent. The friction factor for the bed and plants, f_b, was then calculated with Equation 12.

$$f_b \quad = \quad f + \frac{2Y_o}{b}\left(f - f_w\right) \tag{12}$$

Here b is the width of the channel, and Y_o is the flow depth. The hydraulic radius associated with the bed and plants, R_b, was determined by Equation 13.

$$\frac{R_b}{f_b} \quad = \quad \frac{R_w}{f_w} \quad = \quad \frac{R_h}{f} \tag{13}$$

R_w is the hydraulic radius for the walls; and R_h is the total hydraulic radius. Equations 12 and 13 are from Vanoni and Brooks (1957). Finally, the Manning's coefficient n_b for the bed and vegetation roughness was calculated using R_b in Equation 1.

The coefficient n_b is the resistance of both the bed and vegetation roughness. Equation 14 can be used to calculate the resistance coefficient n_{veg} for the net resistance of the vegetation.

$$\mathrm{n}_{veg} \quad = \quad \mathrm{n_b} - \mathrm{n_o} \tag{14}$$

where n_{veg} is the Manning's coefficient for vegetation; n_b is the bed and vegetation resistance; and n_o is the bed roughness. The value for n_o for both the clay and mortar beds (corrected for wall effects) was determined to be approximately 0.020. V_*/V was found to have a value of 0.069. Resistance coefficients reported in this report show the combined value for the bed and the plants. This combined value is typically reported in field investigations. Roughness coefficients reported herein may be reduced to strictly vegetation roughness coefficients by subtracting 0.020 from reported Manning's n values and 0.069 from reported V_*/V values.

Measured Drag Forces

Drag forces were measured in both the large and small flumes. More than 100 experiments were conducted in the small flume using 10 different plant types, and more than 20 experiments were conducted in the large flume using four plant types. Measured approach velocities and drag forces are shown in Tables 7 and 8 for the small and large flumes, respectively. Data from four different dogwood plants are plotted in Figure 13 showing the repeatability of drag force measurements between the large and small flumes. This is important because it demonstrated that the experimental data from the small flume could be directly compared to the plants and resistance coefficients determined in the large flume. In Figure 13, note that the drag force increases linearly with velocity instead of with the square of velocity as one would expect from the drag force equation (15). This occurred in the experiment because the drag coefficient and blockage area were reduced as the plant was streamlined by the increasing velocities.

$$F_D = \frac{\rho C_D A_i V_p^2}{2} \qquad (15)$$

In Equation 15, F_D is the drag force, ρ is the density of water, C_D is the drag coefficient, V_P is the approach velocity, and A_i is the blockage area of an individual plant.

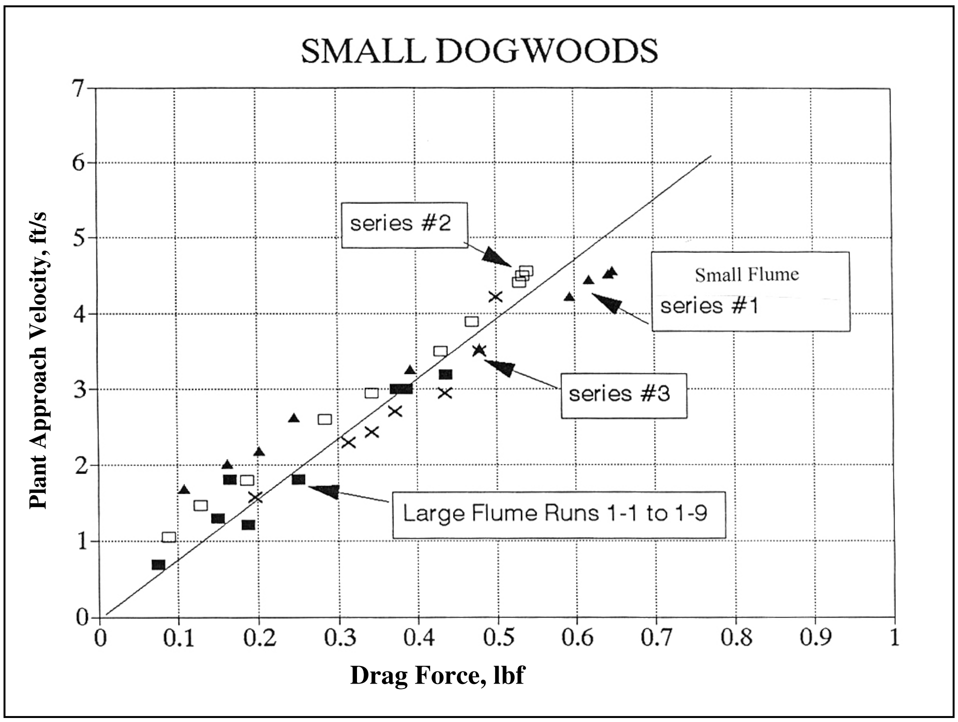

Figure 13. Plant approach velocity versus drag force (To convert feet to meters, multiply by 0.3048) [To convert pounds (force) to newtons, multiply by 4.448222]

The small flume had a large plastic window through which plant distortion could be viewed and measured. It was observed that the plants easily bent with the flow, and the leaf mass trailed downstream forming a streamlined, almost teardrop-shaped profile. The leaf mass changed with velocity and became more streamlined with increased velocity. This observation explains the significant decrease in resistance with increase in velocity. The changing shape of the leaf mass means that the roughness coefficient will change with velocity and that the assignment of a constant roughness coefficient to determine a stage-discharge curve would be invalid and produce significantly incorrect results.

If plant resistance were constant with increasing velocities, a plot of velocity versus drag force would appear as a smooth exponentially increasing curve. A typical curve from the data is shown in Figure 14. In this figure the drag varies almost linearly with velocity as the leaf mass continues to streamline. At a velocity of about 1.2 m/sec (4 ft/sec) the leaf mass has reached its streamlining limit and the curve begins to take on the expected exponential form. Above this limiting velocity it would be appropriate to assign a constant roughness coefficient.

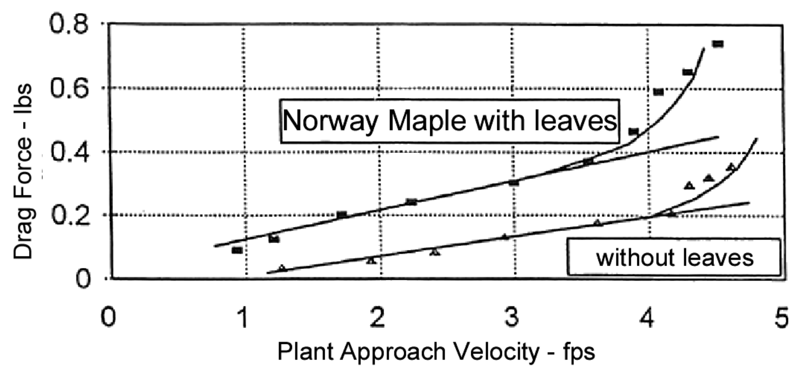

Figure 14. Drag force versus velocity (To convert feet to meters, multiply by 0.3048) [To convert pounds (force) to newtons, multiply by 4.448222]

Development of Resistance Methodology

The methodology developed in this report was based on the premise that the flow resistance due to vegetation on a floodplain is equal to the sum of the total drag forces produced by that vegetation. Kadlec (1990) presented such a hypothesis and, assuming that the drag forces on the bed are negligible, gave the following conceptual equation relating shear stress to drag force.

$$\tau_o = \sum \frac{F_D}{area} = F_D M \qquad (16)$$

where

area = total bed surface area of interest

τ_o = shear stress ($\tau_o = \gamma R_h S$)

M = plant density

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

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

The shear velocity and shear stress can then be related to drag force by using Equation 17:

$$V_* = \sqrt{\frac{\tau_o}{\rho}} = \sqrt{\frac{F_D M}{\rho}} \tag{17}$$

Using Equations 15 through 17, an equation relating the drag coefficient, C_D, to the resistance can be developed.

$$\frac{V_*}{V} = \left(\frac{A_i \ M \ C_D}{2}\right)^{0.5} \tag{18}$$

The blockage area, A_i, of a plant with dense foliage is approximated by multiplying the effective plant height times the effective plant width ($H' \times W_e$). This effective area is the equivalent rectangular area of the leaf mass discounting small stems that are not part of the average leaf mass. For plants that have voids in their leaf mass or few leaves with a large number of stems, A_i is the rectangular area equivalent to the net frontal blockage. For example, plants without leaves would have a blockage area equal to the number of stems times the stem diameter times the stem length. Blockage areas for the laboratory experiments were determined from digital photographs of the plant against a white background marked with grid lines. H' is the actual height of the undistorted leaf mass and W_e is the effective width that produces the measured A_i.

It has been established that the drag coefficient for a rigid body is not a constant and varies with Reynolds number, R_e. The Reynolds number used in this study is based on the length variable of hydraulic radius, R_h, and the mean channel velocity. For flexible plants, the drag coefficient is a function of a number of factors as shown in Equation 19.

$$C_D = f\left(R_e,\ Y_o, H, \text{plant type, plant shape, plant flexibility}, M\right) \tag{19}$$

The experimental data from both the large and small flumes were used to determine appropriate dimensionless parameters to define the drag force. These experiments were conducted for a large matrix of variables including Y_o, V, plant type, leaf density, plant density, plant shape, plant size, and blockage area. The runs were made in a sequence so that each variable could be evaluated by keeping the other variables constant. It was found that the drag coefficient decreased with an increase in velocity, depth, plant density, plant flexibility, and plant spacing. Drag coefficient or resistance could not be related solely to flow conditions, leaf density, or plant blockage because of the flexibility of the plants. For example, different plants with the same size leaves and blockage had significantly different resistance depending upon how much the plants deformed and bent with flow.

Dimensional analysis was used to aid in the selection of dimensionless parameters that could relate drag or resistance to flow and plant variables. The four parameters that were found to have a significant effect were as follows:

a. Ratio of the flow drag force to the forces resisting plant distortion.

b. Ratio of the flow depth to the plant height.

c. Blockage of the plants to the flow on the channel bottom.

d. Reynolds number.

The last three parameters are corrections or modifiers to the ratio parameter of drag force to the force resisting plant deformation. This ratio parameter also incorporates plant stiffness or flexibility. These parameters are shown in Equation 20.

$$C_D \ or \ \frac{V_*}{V} \quad = \quad f\left(\frac{\rho V^2 A_i}{E_s A_s},\ \frac{Y_o}{H},\ M\, A_i,\ R_e\right) \tag{20}$$

When there are several stems emerging from the base of the plant, the stiffness modulus, E_s, is determined for a single stem. The stem area, A_s, is the sum of all the stem areas. The stem area for a plant with multiple stems is thus calculated as the number of stems times π times the stem diameter squared divided by 4.

Resistance Equation for Submerged Vegetation

The results from the large flume experiments were analyzed to determine the regression of the variables of Equation 20 for submerged vegetation. The regression analysis found that log and polynomial relationships gave a poor data fit while a power relationship had very good results. Equations 21 and 22 were found to fit the data with a regression coefficient of R^2 = 96 percent and a maximum scatter of 15 percent for predicted values of V_*/V with measured values. The parameters in the equations were modified to allow a direct solution for resistance (for a given depth) by combining the original parameters with Manning's equation and the equation for shear velocity. This modification and combination of equations resulted in Equations 21 for shear velocity and Equation 22 for Manning's n.

$$\frac{V_*}{V} = \frac{\sqrt{g}}{C} = 0.183 \left(\frac{E_s A_s}{\rho A_i V_*^2} \right)^{0.183} \left(\frac{H}{Y_O} \right)^{0.243} \left(M\ A_i \right)^{0.273} \left(\frac{\nu}{V_* R_h} \right)^{0.115} \qquad (21)$$

$$n = K_n\ 0.183 \left(\frac{E_s\ A_s}{\rho\ A_i\ V_*^2} \right)^{0.183} \left(\frac{H}{Y_O} \right)^{0.243} \left(M\ A_i \right)^{0.273} \left(\frac{\nu}{V_* R_h} \right)^{0.115} \left(\frac{1}{V^*} \right) \left(R_h \right)^{2/3} \left(S \right)^{1/2} \qquad (22)$$

It is important to note that the plant characteristics H, A_i, and A_S are the initial characteristics of the plants without the effects of flow distortion. During the experiments, it was observed that since the plants bent with flow, submergence occurred when flow depths reached 80 percent of the plant height. Equations 21 and 22 are to be applied only for submerged flow defined by Y_o >0.8 H. Equations 23 and 24 are for partially submerged flow with Y_o <0.8 H. Both sets of equations converged to approximately the same result at the flow depth Y_o =0.8 H.

Resistance Equation for Partially Submerged Vegetation

The data for partially submerged vegetation were analyzed to determine the regression of the variables of Equation 20. The regression analysis again found that a log relationship gave a poor fit of data while a power relationship produced very good results. Equations 23 and 24 were found to fit the data with a regression coefficient of R^2= 85 percent and a maximum scatter of 18 percent for predicted values of V_*/V compared to measured values. These equations again allow direct solution for resistance if the flow depth is known.

$$\frac{V_*}{V} = \frac{\sqrt{g}}{C} = 3.487E-05 \left(\frac{E_s A_s}{\rho A_i^* V_*^2} \right)^{0.150} \left(M A_i^* \right)^{0.166} \left(\frac{V_* R_h}{\upsilon} \right)^{0.622} \qquad (23)$$

$$\text{n} = K_n\ 3.487E-05 \left(\frac{E_s\ A_s}{\rho\ A_i^*\ V_*^2} \right)^{0.150} \left(M\ A_i^* \right)^{0.166} \left(\frac{V_* R_h}{\nu} \right)^{0.622} \left(\frac{R_h^{2/3}\ S^{1/2}}{V_*} \right) \qquad (24)$$

The blockage area in Equations 23 and 24 was changed to an effective area, A_{i*}, since only a portion of the leaf mass produces blockage under partially submerged flow conditions. The effective blockage area can be approximated using Equation 25 if the actual geometry of the plant and leaf mass has not been measured (see Figure 2).

$$A_i^* \quad = \quad \left[Y_o - \left(H - H'\right)\right] W_e \qquad (25)$$

The analysis of data and the regression fit of Equations 21 through 24 included many other parameters and ratios. The equations, parameters, and methods developed by other researchers for a combined density and blockage of heavy ground cover and grasses did not produce satisfactory results. These methods included those developed by Kowen and Li (1980), Ree and Crow (1977), and other methods. It should be noted that some of the methods evaluated were not developed with shrubs in mind. In the case of Ree and Crow, agricultural crops were the focus of the methodology. Many of the equations developed by other researchers were evaluated, but none proved to be satisfactory in the prediction of roughness values for shrubs. The results of this study emphasize that the plant stiffness modulus, E_s, must be considered to obtain a satisfactory prediction of roughness. The definition and method to determine E_s are discussed in a following section.

Equations 21 through 24 also include plants with multiple stems. The blockage area A_i 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 individual average plant. Figure 15 shows the correlation of calculated V_*/V with the observed data from the flumes for submerged, partially submerged, multiple plant species.

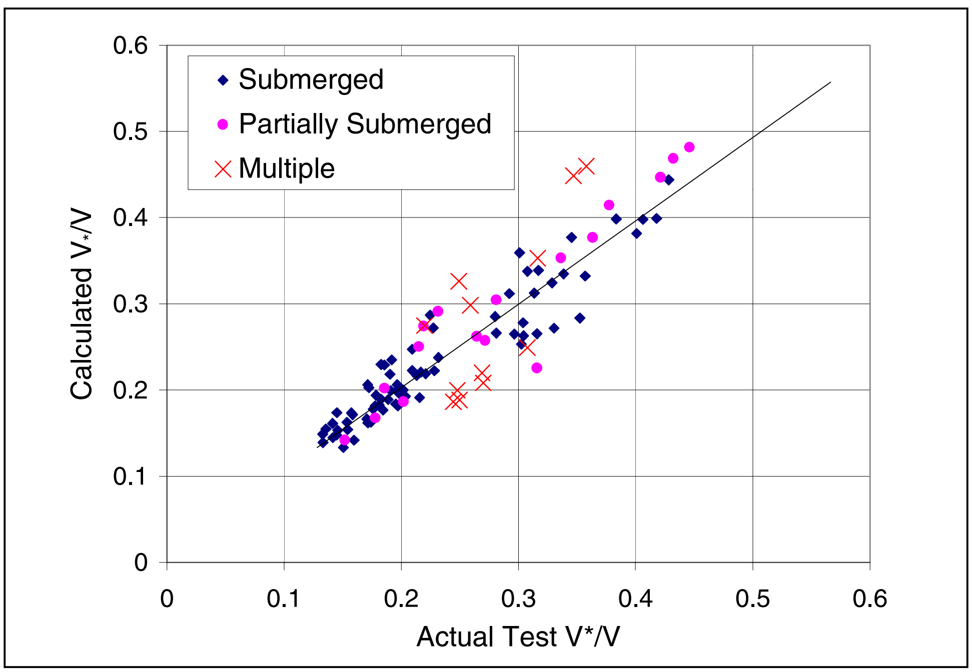

Figure 15. Comparison of calculated versus actual resistance V_*/V

Multiple Plant Combinations

Six combinations of plant types were evaluated. The combinations of species were selected to represent typical plant groups found in different ecosystems. Equations 21 through 24 worked equally well for plant combinations when average plant characteristics were used. The average plant characteristics were obtained by weighting individual plant characteristics by the number of plants per unit area or densities of each type of plant. The comparisons of calculated and observed data for multiple plant groupings are shown in Figure 15.

The purpose of the weighted averages is to formulate the average shear stress created by the plant combinations. Each plant group then will have an average blockage area or effective blockage area, an average modulus of plant stiffness, an average total plant stem area, an average plant height, and an average effective plant height. A weighted average for the plant groups is then based on the ratio of the plant density of each plant type divided by the total plant density of all the plants and plant types. Equations 21 through 24 do not use an average plant density, but use the total or combined density of all of the plants. The method for combining these densities is shown in the example that follows.

The plant characteristics are determined by weighting the individual plant characteristics according to their relative density in the area of interest. The weighted values are then summed to obtain the combined plant characteristic as shown in Equations 26-32.

$$A_{ave} = \sum_{i=1}^{N}\left(A_i \frac{M_i}{M_{total}}\right) \tag{26}$$

$$E_{s\,ave} = \sum_{i=1}^{N}\left(E_{s\,i} \frac{M_i}{M_{total}}\right) \tag{27}$$

$$A_{s\,ave} = \sum_{i=1}^{N}\left(A_{s\,i} \frac{M_i}{M_{total}}\right) \tag{28}$$

$$H_{ave} = \sum_{i=1}^{N}\left(H_i \frac{M_i}{M_{total}}\right) \tag{29}$$

$$H'_{ave} = \sum_{i=1}^{N}\left(H'_i \frac{M_i}{M_{total}}\right) \tag{30}$$

$$A^*_{i\,ave} = \sum_{i=1}^{N}\left(A^*_{i\,i} \frac{M_i}{M_{total}}\right) \tag{31}$$

$$M_{total} = \sum_{i=1}^{N} M_i \quad (32)$$

Using Equation 29, the average plant height for an area with a group of three plants with heights, H, of 0.5, 1.0, and 2.0 ft; and densities, M, of 0.25, 0.50, and 0.20 plants / ft^2; would be determined as follows:

$$Havg = H_1 \text{ x } M_1 / M_{total} + H_2 \text{ x } M_2 / M_{total} + H_3 \text{ x } M_3 / M_{total}$$

Havg = 0.5 x 0.25 / (0.25+0.5+0.2) +1.0 x 0.5 / 0.95 + 2.0 x 0.2 / 0.95

Havg = 0.132 + 0.526 + 0.421 = 1.079 ft

Stiffness Modulus

The modulus of plant stiffness, E_s, is critical to the calculation of resistance because of the flexibility of the plants and the deformation of leaf masses due to the flow forces. The modulus of plant stiffness is calculated by Equation 33.

$$E_S = \frac{F_{45} H^2}{3 I} = 6.791 \left(\frac{F_{45} H^2}{D_S^4} \right) \quad (33)$$

The data necessary to use Equation 33 is obtained by measuring the force, F_{45}, necessary to bend the plant to an angle of 45 deg. The 45-deg angle is measured from the initial vertical position to the stem or leaf mass at the point where the force is measured, i.e., at H/2 as shown in Figure 16.

I is the second area moment of inertia calculated for a circular shape ($I = \pi D_s^4/64$). The stem diameter D_s is measured at a height of H/4 above the ground.

Data were collected both in the laboratory and in the field to determine a relationship that defined plant stiffness. Freeman (1997) collected data for five types of willows in floodplains and on sand bars to determine if stiffness in the field could be predicted from plant size parameters such as stem diameter and plant height to reduce the number of parameters that must be collected to determine the plant stiffness modulus. Data collected included samples from *Salix exigua* willows in Utah and Idaho, *Salix lasiandra, Salix lamonii*, a wild rose bush common to the area, and young cottonwood trees growing on sandbars. He also noted in his data collection efforts that plant stiffness was measurably different in the upstream and downstream directions in streams subject to long periods of high water (i.e., snow melt). Where the plants were not subject to velocities high enough to keep the plant bent and /or deformed for prolonged periods of time this difference in the stiffness modulus did not seem to exist or was not noticeable.

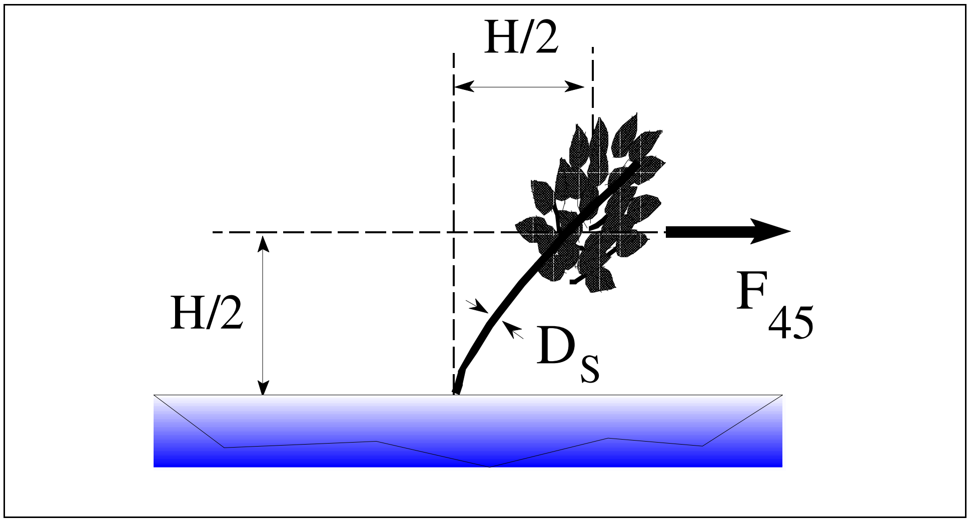

Figure 16. Methodology for measurement of plant stiffness for calculation of E_s in the field for plants with effective height of leaf mass approximately equal to the plant height

The research performed in the laboratory and in the field indicated that the stiffness modulus can be estimated from the relationship of E_s to the ratio of H/D_s. The analysis of measurements made in the field and in the laboratory led to the development of Equations 34 and 35 to explain the relationship between H/D_s and E_s. The relationship between the data observed in Freeman's field measurements (Freeman 1997, Freeman, et al. 1998) and the values predicted by Equation 34 is shown in Figure 17. Equation 34 (shown in Figure 17 as "Rahmeyer Predicted") was developed based on laboratory observations and gives the modulus in pounds per square foot while Equation 35 gives the value in newtons per square meter. It must be cautioned that the fit of Equations 34 and 35 have a regression (R^2) of less than 90 percent, and the scatter is significant as shown in Figure 17.

$$E_s\left(\frac{lbf}{ft^2}\right)=1.597E05\left(\frac{H}{D_S}\right)+454\left(\frac{H}{D_S}\right)^2 37.8\left(\frac{H}{D_S}\right)^3 \quad (34)$$

$$E_s\left(\frac{N}{m^2}\right)=7.648E06\left(\frac{H}{D_S}\right)+2.174E04\left(\frac{H}{D_s}\right)+1.809E03\left(\frac{H}{D_S}\right) \quad (35)$$

Actual field measurements of E_s are recommended where possible. The stiffness modulus can also be estimated from measured values of similar plants. Since the stiffness modulus varies depending on the plant size, it was determined that if the calculated modulus for a particular plant size was divided by $(H/D_s)^{1.5}$, the stiffness modulus became independent of plant size and one value could be used for all plant sizes. Thus, to calculate the plant stiffness modulus for Alder, the value from Table 9 is multiplied by $(H/D_s)^{1.5}$ which gives the stiffness modulus

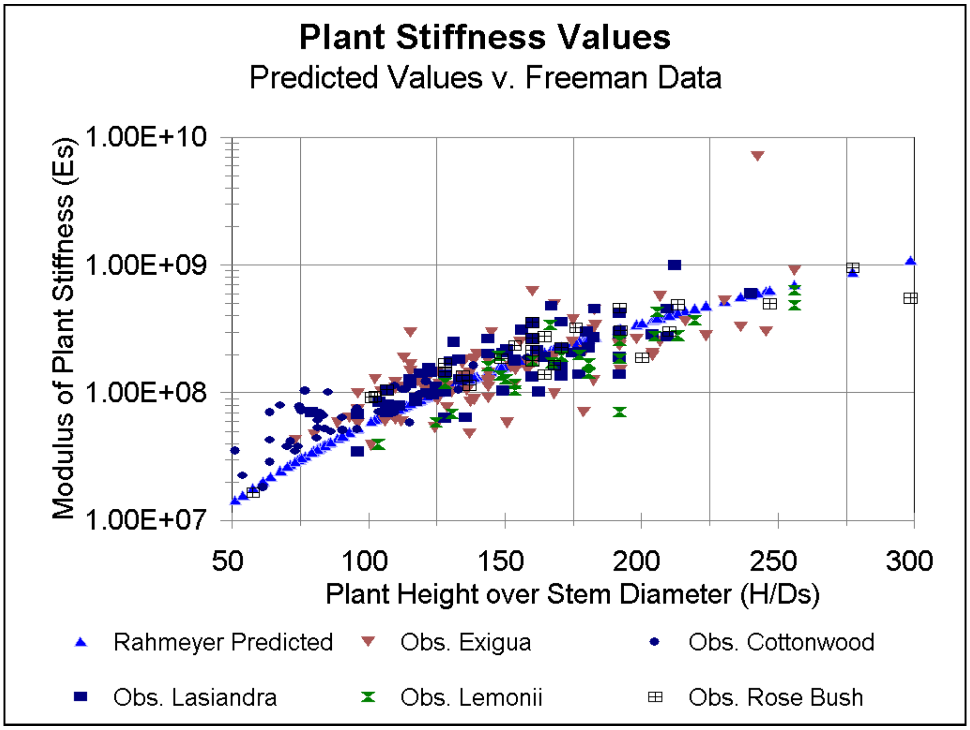

Figure 17. Measured versus calculated plant stiffness modulus, E_s

for a particular size plant in pounds per square foot. The exponent for the term H/D_s was determined to remove most effects of plant size from the Plant Stiffness Modulus.

4 Conclusions

A total of 20 different plant species were evaluated in either a large 2.44-m- (8-ft-) wide flume or a small 0.46-m- (1.5-ft-) wide flume to determine flow resistance and drag force. More than 220 experiments were conducted. Fifteen homogeneous plant groupings were evaluated in the large flume. Six multiple plant groupings were evaluated in the large flume. Vegetation was evaluated under both submerged and partially submerged conditions. Velocity, depths, plant density, plant dimensions, and plant types were varied in the experiments. The range of experimental conditions used to develop the regression equations were as follows:

a. Flow depths from 0.4 to 1.4 m (1.3 to 4.7 ft).

b. Average flow velocities from 0.15 to 1.1 m/s (0.5 to 3.6 ft/s).

c. Measured resistance V_*/V from 0.13 to 0.43 and n from 0.04 to 0.14.

d. Plant heights from 0.20 to 1.52 m (0.66 to 5 ft).

e. Plant widths from 0.076 to 0.91 m (0.25 to 3 ft).

f. Plant densities from 0.53 to 13 plants / m^2 (0.05 to 1.2 plants / ft^2).

g. Plant modulus of stiffness from 5.3×10^7 to 4.8×10^9 N/m^2 (1.1×10^6 to 1.0×10^8 lbf/ ft^2).

h. Reynolds numbers from 1.4×10^5 to 1.6×10^6.

An important observation made during the flume studies was that the plant leaf mass trailed downstream forming a streamlined, almost teardrop-shaped profile. The leaf mass shape changed with velocity and became more streamlined with increasing velocity. The effect of this phenomenon was a significant decrease in the drag coefficient and resistance coefficient with velocity. On the other hand, resistance increased with depth for partially submerged plants as the blockage area increased with depth until the plants were submerged. The transition between submerged and partially submerged flow occurred at a depth of about 80 percent of the undeflected plant height.

Another observation made during the study was that the leaf mass or foliage canopy diverted flow beneath the canopy. The bottom flow resulted in significant velocities along the channel bed causing general scour and increased sediment transport. The bed velocities were sufficient to transport and move the largest sizes of gravel found in the flume bed.

The hydraulic roughness of a vegetated channel was shown to be a function of the stiffness of the plants growing in the channel, the depth, velocity, and hydraulic radius of the channel, plant density, and frontal area of the plant obstructing the flow. It was determined that the roughness can be calculated directly if the depth of flow is known. The roughness can be determined in terms of Manning's n, Chezy C, or the shear velocity ratio, V_*/V.

Regression equations were developed for submerged vegetation and found to fit the data with a regression coefficient of R^2 = 96 percent and a maximum scatter of 15 percent for predicted values of V_*/V with measured values. The parameters in the equations were modified to allow a direct solution for resistance (for a given depth) by combining the original parameters with Manning's equation and the equation for shear velocity. This modification and combination of equations resulted in Equations 21 for shear velocity and Equation 22 for Manning's n.

$$\frac{V_*}{V} = \frac{\sqrt{g}}{C} = 0.183 \left(\frac{E_s A_s}{\rho A_i V_*^2} \right)^{0.183} \left(\frac{H}{Y_O} \right)^{0.243} (M\ A_i)^{0.273} \left(\frac{\nu}{V_* R_h} \right)^{0.115} \qquad (21)$$

$$n = K_n\ 0.183 \left(\frac{E_s\ A_s}{\rho\ A_i\ V_*^2} \right)^{0.183} \left(\frac{H}{Y_O} \right)^{0.243} (M\ A_i)^{0.273} \left(\frac{\nu}{V_* R_h} \right)^{0.115} \left(\frac{1}{V^*} \right) (R_h)^{2/3} (S)^{1/2} \qquad (22)$$

It is important to note that the plant characteristics H, A_i, and A_S are the initial characteristics of the plants without the effects of flow distortion. Equations 21 and 22 are to be applied only for submerged flow defined by $Y_o > 0.8$ H.

The experimental data for partially submerged vegetation were analyzed to develop regression Equations 23 and 24. These equations were found to fit the data with a regression coefficient of R^2= 85 percent and a maximum scatter of 18 percent for predicted values of V_*/V compared to measured values. These equations again allow direct solution for resistance if the flow depth is known.

$$\frac{V_*}{V} = \frac{\sqrt{g}}{C} = 3.487E-05 \left(\frac{E_s\ A_s}{\rho\ A_i^*\ V_*^2} \right)^{0.150} (M\ A_i^*)^{0.166} \left(\frac{V_*\ R_h}{\nu} \right)^{0.622} \qquad (23)$$

$$n = K_n\ 3.487E-05 \left(\frac{E_s\ A_s}{\rho\ A_i^*\ V_*^2} \right)^{0.150} (M\ A_i^*)^{0.166} \left(\frac{V_* R_h}{\nu} \right)^{0.622} \left(\frac{R_h^{2/3}\ S^{1/2}}{V_*} \right) \qquad (24)$$

The blockage area in Equations 23 and 24 was changed to an effective area, A_{i*}, since only a portion of the leaf mass produces blockage under partially submerged flow conditions. The effective blockage area can be approximated using Equation 25 if the actual geometry of the plant and leaf mass has not been measured.

$$A_i^* = \left[Y_o - \left(H - H'\right)\right] W_e \tag{25}$$

The resistance coefficients predicted by Equations 21 through 24 represent the combined resistance of the bed and the plants. Resistance coefficients due only to vegetation must be calculated by subtracting the bed resistance. In these experiments the Manning's bed resistance coefficient was found to be 0.02 and V_*/V for the bed was found to be 0.069.

The modulus of plant stiffness, E_s, is critical to the calculation of resistance because of the flexibility of the plants and the deformation of leaf masses due to the flow forces. The research performed in the laboratory and in the field indicated that the stiffness modulus can be estimated from the relationship of E_S to the ratio of H/D_s. The analysis of measurements made in the field and in the laboratory led to the development of equations to explain the relationship between H/D_s and E_s. The equations had a regression (R^2) of less than 90 percent. Actual field measurements of E_s are recommended where possible.

The stiffness modulus can also be estimated from measured values of similar plants. Since the stiffness modulus varies depending on the plant size, it was determined that if the calculated modulus for a particular plant size was divided by $(H/D_s)^{1.5}$, the stiffness modulus became independent of plant size and one value could be used for all plant sizes. Stiffness modulus' of plants used in this study are provided in Table 9.

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Table 1
Dimensions and Characteristics of Plants (SI Units)

Common Name	**Scientific Name**	**Plant Height *H*, m**	**Plant Width *We*, m**	**Effective Height, *H*', m**	**Blockage Area *A* m^2**	**Stem Diameter *Ds*, M**	**Stem Number**	**Elasticity *Es*, $N/m^2 x10^8$**
				Large Flume				
Yellow Twig Dogwood	*Cornus Stolonifera Flaviramea*	0.51	0.229	0.33	0.076	0.0095	1	3.210
Berried Elderberry	*Sambucus Racemosa*	0.71	0.356	0.51	0.181	0.0095	1	0.526
Purpleleaf Euonymus	*Euonymus Fortunei Colorata*	0.20	0.254	0.20	0.052	0.0063	2	4.140
Red Twig Dogwood	*Cornus Sericea*	0.97	0.482	0.76	0.368	0.0252	2	10.200
Service Berry	*Amelanchier*	0.71	0.178	0.51	0.090	0.0063	6	47.600
Yellow Twig Dogwood	*Cornus Stolonifera Flaviramea*	0.71	0.254	0.61	0.155	0.0095	2	29.900
Mulefat	*Baccharis Glutinosa*	0.97	0.076	0.51	0.039	0.0126	1	5.950
Alder	*Alnus Incana*	0.76	0.152	0.70	0.107	0.0079	1	17.000
Valley Elderberry	*Sambucus Mexicana*	0.97	0.762	0.91	0.697	0.0268	1	16.500
Salt Cedar	*Tamarix spp.*	1.52	0.61	1.37	0.836	0.0316	1	13.100
Black Willow	*Salix Nigra*	1.22	0.305	1.22	0.372	0.0189	1	1.500
Red Willow	*Salix spp.*	0.61	0.152	0.61	0.093	0.0095	1	4.500
Mountain Willow	*Salix Monticola*	1.52	0.914	1.22	1.115	0.0254	4	3.410
				Small Flume				
Yellow Twig Dogwood	*Cornus Stolonifera Flaviramea*	0.51	0.229	0.33	0.076		0.0095	3.210
Purpleleaf Eunonyus	*Euonymus Fortunei Colorata*	0.20	0.254	0.20	0.052	0.0063	2	4.140
Artic Blue Williow	*Salix Purpurea Nana*	0.56	0.305	0.51	0.155	0.0126	1	1.190
Norway Maple	*Acer Platenoides*	0.71	0.305	0.30	0.093	0.0126	1	19.100
Common Privet	*Ligustrum Vulgare*	0.81	0.254	0.69	0.174	0.0126	1	3.940
Blue Elderberry	*Sambucus Canadensis*	0.53	0.457	0.41	0.186	0.0252	1	0.263
French Pink Pussywillow	*Salix Caprea Pendula*	0.91	0.254	0.25	0.065	0.0190	1	1.110
Sycamore	*Platenus Acer Ifolia*	0.91	0.203	0.84	0.170	0.0101	1	27.500
Western Sand Cherry	*Prunis Besseyi*	0.74	0.152	0.51	0.077	0.0084	1	28.800
Staghorn Sumac	*Rhus Typhina*	0.76	0.254	0.31	0.077	0.0126	1	5.080
Sand Bar Willow	*Salix exigua*	2.18		1.8	0.65	0.015	1	86.2
Pacific Willow	*Salix lasiandra*	2.39		2.0	1.98	0.017	1	99.0
Lemon's Willow	*Salix Lemonii*	2.13		1.7	0.38	0.013	1	86.0
Wild Rose Bush	*Rosa spp.*	1.18		.108	1.05	0.007	1	130.0

Table 2
Dimensions and Characteristics of Plants (Non-SI Units)

Common Name	Scientific Name	Plant Height *H*, ft	Plant Width *We*, ft	Effective Height, *H'*, ft	Blockage Area *A* Ft^2	Stem Diameter *Ds*, ft	Stem Number	Elasticity *Es*, lbf/ft^2
Large Flume								
Yellow Twig Dogwood	Cornus Stolonifera Flaviramea	1.67	0.750	1.08	0.818	0.0313	1	6.706
Berried Elderberry	Sambucus Racemosa	2.33	1.167	1.67	1.948	0.0313	1	1.099
Purpleleaf Euonymus	Euonymus Fortunei Colorata	0.67	0.833	0.67	0.560	0.0208	2	8.648
Red Twig Dogwood	Cornus Sericea	3.18	1.583	2.50	3.958	0.0833	2	21.308
Service Berry	Amelanchier	2.33	0.583	1.67	0.969	0.0208	6	99.436
Yellow Twig Dogwood	Cornus Stolonifera Flaviramea	2.33	0.833	2.00	1.666	0.0313	2	62.461
Mulefat	Baccharis Glutinosa	3.18	0.250	1.67	0.420	0.0420	1	12.430
Alder	Alnus Incana	2.50	0.500	2.33	1.150	0.0260	1	35.513
Valley Elderberry	Sambucus Mexicana	3.18	2.500	3.00	7.503	0.0879	1	34.469
Salt Cedar	Tamarix spp.	5.00	2.000	4.50	9.001	0.1040	1	27.366
Black Willow	Salix Nigra	4.00	1.000	4.00	4.005	0.0630	1	3.134
Red Willow	Salix spp.	2.00	0.500	2.00	1.001	0.0310	1	9.401
Mountain Willow	Salix Monticola	5.00	3.000	4.00	12.003	0.0840	4	7.123
Small Flume								
Yellow Twig Dogwood	Cornus Stolonifera Flaviramea	1.67	0.750	1.08	0.818	0.0313	1	6.706
Purpleleaf Eunonyus	Euonymus Fortunei Colorata	0.67	0.833	0.67	0.560	0.0208	2	8.648
Artic Blue Williow	Salix Purpurea Nana	1.84	1.000	1.67	1.669	0.0417	1	2.486
Norway Maple	Acer Platenoides	2.33	1.000	1.00	1.001	0.0417	1	39.900
Common Privet	Ligustrum Vulgare	2.67	0.833	2.25	1.873	0.0417	1	8.231
Blue Elderberry	Sambucus Canadensis	1.75	1.500	1.33	1.997	0.0833	1	0.549
French Pink Pussywillow	Salix Caprea Pendula	3.00	0.833	0.83	0.700	0.0625	1	2.319
Sycamore	Platenus Acer Ifolia	3.00	0.667	2.75	1.831	0.0333	1	57.448
Western Sand Cherry	Prunis Besseyi	2.43	0.500	1.67	0.829	0.0278	1	60.163
Staghorn Sumac	Rhus Typhina	2.50	0.833	1.00	0.829	0.0417	1	10.612
Sand Bar Willow	Salix exigua	7.15		5.91	7.09	0.0492	1	180
Pacific Willow	Salix lasiandra	7.84		6.56	21.31	0.0558	1	207
Lemon's Willow	Salix lemonii	7.0		5.58	4.09	0.0427	1	180
Wild Rose Bush	Rosa spp.	3.87		0.354	11.30	0.0230	1	272

Table 3
Summary of Large Flume Results with Homogeneous Groupings (SI Units)

Run	Plant	Plant Height *H*, m	Plant Density *M*, 1/m^2	Water Depth Y_o, M	Mean Velocity *V*, m/sec	Energy Slope *S*	Average *n*	Bed Hydraulic Radius *m*	Bed *V*/V*	Bed Manning's n
II 0-1	none			0.718	0.388	0.00013		0.562	0.069	0.0200
II 0-2	none			1.321	0.209	0.00002	0.016	0.884	0.064	0.0200
II 0-3	none			1.459	0.591	0.00015	0.016	1.011	0.069	0.0220
I 1-1	Yellow Twig Dogwood	0.51	5.360	1.271	0.366	0.00053	0.046	1.202	0.216	0.0710
I 1-2	Yellow Twig Dogwood	0.51	5.360	1.256	0.610	0.00124	0.042	1.184	0.198	0.0650
I 1-3	Yellow Twig Dogwood	0.51	5.360	1.122	0.750	0.00184	0.040	1.059	0.185	0.0590
I 1-4	Yellow Twig Dogwood	0.51	5.360	0.942	0.482	0.00119	0.047	0.902	0.213	0.0670
I 1-5	Yellow Twig Dogwood	0.51	5.360	1.021	0.588	0.00140	0.043	0.971	0.196	0.0620
I 1-6	Yellow Twig Dogwood	0.51	5.360	1.049	0.689	0.00163	0.040	0.991	0.183	0.0580
I 1-7	Yellow Twig Dogwood	0.51	5.360	0.536	0.878	0.00582	0.048	0.521	0.197	0.0560
I 1-8	Yellow Twig Dogwood	0.51	5.360	0.716	0.991	0.00477	0.041	0.688	0.181	0.0540
I 1-9	Yellow Twig Dogwood	0.51	5.360	0.887	1.091	0.00418	0.038	0.843	0.170	0.0530
I 2-1	Yellow Twig Dogwood	0.51	2.379	1.356	0.765	0.00102	0.031	1.232	0.145	0.0480
I 2-2	Yellow Twig Dogwood	0.51	2.379	1.149	0.924	0.00165	0.031	1.056	0.142	0.0460
I 2-3	Yellow Twig Dogwood	0.51	2.379	0.515	1.058	0.00693	0.040	0.499	0.174	0.0500
I 2-4	Yellow Twig Dogwood	0.51	2.379	0.396	0.750	0.00496	0.042	0.421	0.191	0.0530
I 3-1	Berried Elderberry	0.71	2.691	1.207	0.294	0.00030	0.042	1.134	0.195	0.0640
I 3-2	Berried Elderberry	0.71	2.691	0.983	0.479	0.00063	0.035	0.918	0.157	0.0500
I 3-3	Berried Elderberry	0.71	2.691	1.064	0.589	0.00085	0.034	0.989	0.154	0.0490
I 3-4	Berried Elderberry	0.71	2.691	0.953	0.304	0.00043	0.045	0.908	0.204	0.0640
I 3-5	Berried Elderberry	0.71	2.691	0.706	0.518	0.00125	0.040	0.676	0.176	0.0530
I 3-6	Berried Elderberry	0.71	2.691	0.782	0.614	0.00110	0.033	0.735	0.145	0.0440
I 3-7	Berried Elderberry	0.71	2.691	0.849	0.692	0.00123	0.032	0.793	0.141	0.0430
I 3-8	Berried Elderberry	0.71	2.691	0.816	0.769	0.00167	0.033	0.767	0.146	0.0450
I 3-9	Berried Elderberry	0.71	2.691	0.748	0.862	0.00199	0.031	0.702	0.136	0.0410
I 3-10	Berried Elderberry	0.71	2.691	0.915	0.945	0.00191	0.030	0.849	0.133	0.0410
I 4-1	Purpleleaf Euonymus	0.20	12.809	1.182	0.319	0.00041	0.045	1.120	0.209	0.0680
I 4-2	Purpleleaf Euonymus	0.20	12.809	1.195	0.420	0.00055	0.040	1.122	0.186	0.0600
I 4-3	Purpleleaf Euonymus	0.20	12.809	1.120	0.669	0.00159	0.042	1.063	0.195	0.0630

(Sheet 1 of 3)

Table 3 (Continued)

Run	Plant	Plant Height H, m	Plant Density M, 1/m^2	Water Depth Y_o, M	Mean Velocity V, m/sec	Energy Slope S	Average n	Bed Hydraulic Radius m	Bed V^*/V	Bed Manning's n
I 4-4	Purpleleaf Euonymus	0.20	12.809	0.842	0.662	0.00225	0.045	0.810	0.202	0.0620
I 4-5	Purpleleaf Euonymus	0.20	12.809	0.887	0.766	0.00251	0.042	0.849	0.189	0.0590
I 4-6	Purpleleaf Euonymus	0.20	12.809	0.781	0.974	0.00408	0.041	0.751	0.178	0.0560
I 4-7	Purpleleaf Euonymus	0.20	12.809	0.491	0.817	0.00477	0.042	0.477	0.183	0.0520
I 5-1	Purpleleaf Euonymus	0.20	5.694	1.032	0.411	0.00053	0.038	0.968	0.172	0.0550
I 5-2	Purpleleaf Euonymus	0.20	5.694	1.034	0.632	0.00106	0.035	0.967	0.159	0.0500
I 5-3	Purpleleaf Euonymus	0.20	5.694	0.707	0.963	0.00436	0.040	0.680	0.177	0.0530
I 6-1	Red Twig Dogwood	0.97	1.216	1.263	0.323	0.00110	0.075	1.233	0.357	0.1190
I 6-2	Red Twig Dogwood	0.97	1.216	1.264	0.479	0.00213	0.070	1.233	0.336	0.1110
I 6-3	Red Twig Dogwood	0.97	1.216	1.296	0.611	0.00266	0.062	1.259	0.297	0.0990
I 6-4	Red Twig Dogwood	0.97	1.216	0.940	0.347	0.00204	0.085	0.925	0.390	0.1230
I 6-5	Red Twig Dogwood	0.97	1.216	0.757	0.609	0.00508	0.070	0.744	0.313	0.0950
I 6-6	Red Twig Dogwood	0.97	1.216	0.829	0.953	0.00582		0.804	0.225	0.0693
I 6-7	Red Twig Dogwood	0.97	1.216	0.537	0.683	0.00833	0.070	0.530	0.308	0.0890
I 6-8	Red Twig Dogwood	0.97	1.216	0.934	0.962	0.00540	0.050	0.905	0.227	0.0720
I 7-1	Red Twig Dogwood	0.97	0.527	1.184	0.348	0.00117	0.070	1.155	0.330	0.1080
I 7-2	Red Twig Dogwood	0.97	0.527	0.818	0.504	0.00322	0.070	0.803	0.316	0.0973
II 1-1	Service Berry	0.71	0.538	0.690	0.350	0.00145	0.063	0.676	0.280	0.0840
II 1-2	Service Berry	0.71	0.538	0.967	0.562	0.00180	0.050	0.933	0.228	0.0720
II 1-3	Service Berry	0.71	0.538	0.803	0.685	0.00229	0.043	0.771	0.192	0.0590
II 1-4	Service Berry	0.71	0.538	0.933	0.903	0.00276	0.038	0.886	0.171	0.0540
II 1-5	Service Berry	0.71	0.538	1.154	0.513	0.00132	0.050	1.108	0.234	0.0760
II 1-6	Service Berry	0.71	0.538	1.275	0.688	0.00157	0.042	1.206	0.198	0.0650
II 4-1	Yellow Twig Dogwood		1.830	1.358	0.145	0.00019	0.071	1.316	0.344	0.1150
II 4-2	Yellow Twig Dogwood		1.830	1.389	0.343	0.00059	0.053	1.330	0.254	0.0850
II 4-3	Yellow Twig Dogwood		1.830	1.261	0.608	0.00112	0.040	1.186	0.189	0.0620
II 4-4	Yellow Twig Dogwood		1.830	1.081	0.967	0.00201	0.032	1.003	0.144	0.0460
II 6-1	Mulefat	0.97	0.646	1.423	0.408	0.00040	0.037	1.314	0.177	0.0590
II 6-2	Mulefat	0.97	0.646	1.265	0.643	0.00095	0.035	1.173	0.162	0.0530
II 6-3	Mulefat	0.97	0.646	1.364	0.724	0.00103	0.033	1.252	0.154	0.0510

(Sheet 2 of 3)

Table 3 (Concluded)										
Run	**Plant**	**Plant Height *H*, m**	**Plant Density *M*, 1/m^2**	**Water Depth Y_o, M**	**Mean Velocity *V*, m/sec**	**Energy Slope *S***	**Average *n***	**Bed Hydraulic Radius *m***	**Bed *V*/V***	**Bed Manning's n**
II 6-4	Mulefat	0.97	0.646	1.072	0.791	0.00119	0.030	0.984	0.135	0.0430
II 9-1	Vally Elberberry	0.97	1.722	1.366	0.282	0.00099	0.083	1.337	0.418	0.1350
II 9-2	Vally Elberberry	0.97	1.722	1.330	0.427	0.00163	0.070	1.296	0.339	0.1130
II 9-3	Vally Elberberry	0.97	1.722	1.071	0.522	0.00267	0.068	1.047	0.317	0.1020
II 9-4	Vally Elberberry	0.97	1.722	0.914	0.621	0.00475	0.072	0.897	0.329	0.1030
II 10-1	Salt Cedar	1.52	0.624	1.430	0.416	0.00156	0.072	1.394	0.352	0.1190
II 10-2	Salt Cedar	1.52	0.624	1.378	0.580	0.00238	0.063	1.338	0.305	0.1020
II 10-3	Salt Cedar	1.52	0.624	1.116	0.716	0.00380	0.060	1.085	0.281	0.0910
II 10-4	Salt Cedar	1.52	0.624	0.933	0.685	0.00369	0.058	0.909	0.264	0.0830
II 10-5	Salt Cedar	1.52	0.624	0.844	0.750	0.00513	0.060	0.824	0.272	0.0840
II 10-6	Salt Cedar	1.52	0.624	0.827	0.935	0.00517	0.048	0.801	0.215	0.0660
II	Black Willow	1.22	2.293	1.416	0.313	0.00084		1.090	0.303	0.0980
II	Black Willow	1.22	2.293	1.426	0.551	0.00113		1.337	0.221	0.0740
II	Black Willow	1.22	2.293	1.388	0.763	0.00210		1.312	0.216	0.0720
II	Black Willow	1.22	2.293	0.680	0.688	0.00175		0.637	0.152	0.0450
II	Black Willow	1.22	2.293	0.906	0.910	0.00333		0.874	0.186	0.0580
II	Black Willow	1.22	2.293	0.821	0.789	0.00326		0.794	0.202	0.0620
II	Black Willow	1.22	2.293	0.776	0.726	0.00228		0.743	0.178	0.0540
II 13-1	Mountain Willow	1.52	4.844	0.678	0.628	0.00323	0.052	0.661	0.231	0.0690
II 13-2	Mountain Willow	1.52	4.844	0.605	0.704	0.00414	0.050	0.590	0.219	0.0640
II 13-3	Mountain Willow	1.52	4.844	0.747	0.651	0.00666	0.075	0.736	0.336	0.1020
II 13-4	Mountain Willow	1.52	4.844	0.818	0.609	0.00616	0.080	0.806	0.363	0.1120
II 13-5	Mountain Willow	1.52	4.844	0.934	0.610	0.00584	0.082	0.919	0.378	0.1190
II 13-6	Mountain Willow	1.52	4.844	1.092	0.521	0.00459	0.090	1.076	0.421	0.1360
II 13-7	Mountain Willow	1.52	4.844	1.251	0.446	0.00306	0.090	1.230	0.432	0.1430
II 13-8	Mountain Willow	1.52	4.844	1.326	0.447	0.00283	0.088	1.303	0.428	0.1420
II 13-9	Mountain Willow	1.52	4.844	1.414	0.526	0.00335	0.083	1.387	0.406	0.1370
II 13-10	Mountain Willow	1.52	4.844	1.278	0.600	0.00432	0.080	1.254	0.383	0.1270
II 13-11	Mountain Willow	1.52	4.844	1.382	0.895	0.00549	0.062	1.343	0.301	0.1010
II 14-1	Mt Willow w/o leaves	1.52	4.844	0.874	0.595	0.00379	0.066	0.856	0.299	0.0930
II 14-2	Mt Willow w/o leaves	1.52	4.844	1.376	0.368	0.00136	0.075	1.343	0.364	0.1220

(Sheet 3 of 3)

Table 4
Summary of Large Flume Results with Homogeneous Groupings (Non-SI Units)

Run	Plant	Plant Height *H*, ft	Plant Density *M*, 1/ft^2	Water Depth Y_o, ft	Mean Velocity *V*, ft/s	Energy Slope *S*	Average *n*	Bed Hydraulic Radius ft	Bed *V**/*V*	Bed Manning's n
II 0-1	none		0.000	2.355	1.274	0.00013		1.844	0.069	0.0200
II 0-2	none		0.000	4.334	0.687	0.00002	0.016	2.901	0.064	0.0200
II 0-3	none		0.000	4.788	1.940	0.00015	0.016	3.318	0.069	0.0220
I 1-1	Yellow Twig Dogwood	1.67	0.498	4.170	1.200	0.00053	0.046	3.944	0.216	0.0710
I 1-2	Yellow Twig Dogwood	1.67	0.498	4.120	2.000	0.00124	0.042	3.885	0.198	0.0650
I 1-3	Yellow Twig Dogwood	1.67	0.498	3.680	2.460	0.00184	0.040	3.474	0.185	0.0590
I 1-4	Yellow Twig Dogwood	1.67	0.498	3.090	1.580	0.00119	0.047	2.959	0.213	0.0670
I 1-5	Yellow Twig Dogwood	1.67	0.498	3.350	1.930	0.00140	0.043	3.185	0.196	0.0620
I 1-6	Yellow Twig Dogwood	1.67	0.498	3.440	2.260	0.00163	0.040	3.252	0.183	0.0580
I 1-7	Yellow Twig Dogwood	1.67	0.498	1.760	2.880	0.00582	0.048	1.710	0.197	0.0560
I 1-8	Yellow Twig Dogwood	1.67	0.498	2.350	3.250	0.00477	0.041	2.258	0.181	0.0540
I 1-9	Yellow Twig Dogwood	1.67	0.498	2.910	3.580	0.00418	0.038	2.766	0.170	0.0530
I 2-1	Yellow Twig Dogwood	1.67	0.221	4.450	2.510	0.00102	0.031	4.041	0.145	0.0480
I 2-2	Yellow Twig Dogwood	1.67	0.221	3.770	3.030	0.00165	0.031	3.463	0.142	0.0460
I 2-3	Yellow Twig Dogwood	1.67	0.221	1.690	3.470	0.00693	0.040	1.636	0.174	0.0500
I 2-4	Yellow Twig Dogwood	1.67	0.221	1.300	2.460	0.00496	0.042	1.382	0.191	0.0530
I 3-1	Berried Elderberry	2.33	0.250	3.959	0.963	0.00030	0.042	3.720	0.195	0.0640
I 3-2	Berried Elderberry	2.33	0.250	3.225	1.570	0.00063	0.035	3.011	0.157	0.0500
I 3-3	Berried Elderberry	2.33	0.250	3.490	1.934	0.00085	0.034	3.244	0.154	0.0490
I 3-4	Berried Elderberry	2.33	0.250	3.125	0.996	0.00043	0.045	2.979	0.204	0.0640
I 3-5	Berried Elderberry	2.33	0.250	2.317	1.699	0.00125	0.040	2.219	0.176	0.0530
I 3-6	Berried Elderberry	2.33	0.250	2.565	2.013	0.00110	0.033	2.410	0.145	0.0440
I 3-7	Berried Elderberry	2.33	0.250	2.787	2.270	0.00123	0.032	2.603	0.141	0.0430
I 3-8	Berried Elderberry	2.33	0.250	2.676	2.522	0.00167	0.033	2.516	0.146	0.0450
I 3-9	Berried Elderberry	2.33	0.250	2.454	2.827	0.00199	0.031	2.303	0.136	0.0410
I 3-10	Berried Elderberry	2.33	0.250	3.002	3.102	0.00191	0.030	2.784	0.133	0.0410
I 4-1	Purpleleaf Euonymus	0.67	1.190	3.878	1.048	0.00041	0.045	3.674	0.209	0.0680
I 4-2	Purpleleaf Euonymus	0.67	1.190	3.921	1.377	0.00055	0.040	3.681	0.186	0.0600
I 4-3	Purpleleaf Euonymus	0.67	1.190	3.673	2.195	0.00159	0.042	3.489	0.195	0.0630
I 4-4	Purpleleaf Euonymus	0.67	1.190	2.762	2.172	0.00225	0.045	2.658	0.202	0.0620
I 4-5	Purpleleaf Euonymus	0.67	1.190	2.911	2.512	0.00251	0.042	2.787	0.189	0.0590

(Sheet 1 of 3)

Table 4 (Continued)										
Run	Plant	Plant Height *H*, ft	Plant Density *M*, 1/ft^2	Water Depth Y_o, ft	Mean Velocity *V*, ft/s	Energy Slope *S*	Average *n*	Bed Hydraulic Radius ft	Bed *V*/V*	Bed Manning's n
I 4-6	Purpleleaf Euonymus	0.67	1.190	2.563	3.195	0.00408	0.041	2.463	0.178	0.0560
I 4-7	Purpleleaf Euonymus	0.67	1.190	1.610	2.679	0.00477	0.042	1.565	0.183	0.0520
I 5-1	Purpleleaf Euonymus	0.67	0.529	3.385	1.348	0.00053	0.038	3.177	0.172	0.0550
I 5-2	Purpleleaf Euonymus	0.67	0.529	3.394	2.074	0.00106	0.035	3.172	0.159	0.0500
I 5-3	Purpleleaf Euonymus	0.67	0.529	2.320	3.158	0.00436	0.040	2.231	0.177	0.0530
I 6-1	Red Twig Dogwood	3.17	0.113	4.143	1.059	0.00110	0.075	4.046	0.357	0.1190
I 6-2	Red Twig Dogwood	3.17	0.113	4.148	1.573	0.00213	0.070	4.046	0.336	0.1110
I 6-3	Red Twig Dogwood	3.17	0.113	4.252	2.005	0.00266	0.062	4.129	0.297	0.0990
I 6-4	Red Twig Dogwood	3.17	0.113	3.085	1.139	0.00204	0.085	3.036	0.390	0.1230
I 6-5	Red Twig Dogwood	3.17	0.113	2.485	1.997	0.00508	0.070	2.442	0.313	0.0950
I 6-6	Red Twig Dogwood	3.17	0.113	2.719	3.127	0.00582		2.639	0.225	0.0693
I 6-7	Red Twig Dogwood	3.17	0.113	1.762	2.241	0.00833	0.070	1.739	0.308	0.0890
I 6-8	Red Twig Dogwood	3.17	0.113	3.065	3.157	0.00540	0.050	2.968	0.227	0.0720
I 7-1	Red Twig Dogwood	3.17	0.049	3.885	1.142	0.00117	0.070	3.788	0.330	0.1080
I 7-2	Red Twig Dogwood	3.17	0.049	2.685	1.653	0.00322	0.070	2.635	0.316	0.0973
II 1-1	Service Berry	2.33	0.050	2.265	1.148	0.00145	0.063	2.217	0.280	0.0840
II 1-2	Service Berry	2.33	0.050	3.173	1.844	0.00180	0.050	3.060	0.228	0.0720
II 1-3	Service Berry	2.33	0.050	2.634	2.249	0.00229	0.043	2.531	0.192	0.0590
II 1-4	Service Berry	2.33	0.050	3.062	2.964	0.00276	0.038	2.908	0.171	0.0540
II 1-5	Service Berry	2.33	0.050	3.786	1.684	0.00132	0.050	3.634	0.234	0.0760
II 1-6	Service Berry	2.33	0.050	4.182	2.257	0.00157	0.042	3.958	0.198	0.0650
II 4-1	Yellow Twig Dogwood		0.170	4.455	0.477	0.00019	0.071	4.319	0.344	0.1150
II 4-2	Yellow Twig Dogwood		0.170	4.558	1.124	0.00059	0.053	4.362	0.254	0.0850
II 4-3	Yellow Twig Dogwood		0.170	4.136	1.994	0.00112	0.040	3.892	0.189	0.0620
II 4-4	Yellow Twig Dogwood		0.170	3.546	3.173	0.00201	0.032	3.290	0.144	0.0460
II 6-1	Mulefat	3.17	0.060	4.668	1.339	0.00040	0.037	4.311	0.177	0.0590
II 6-2	Mulefat	3.17	0.060	4.151	2.108	0.00095	0.035	3.848	0.162	0.0530
II 6-3	Mulefat	3.17	0.060	4.474	2.375	0.00103	0.033	4.107	0.154	0.0510
II 6-4	Mulefat	3.17	0.060	3.518	2.594	0.00119	0.030	3.228	0.135	0.0430
II 9-1	Vally Elberberry	3.17	0.160	4.482	0.926	0.00099	0.083	4.387	0.418	0.1350
II 9-2	Vally Elberberry	3.17	0.160	4.365	1.400	0.00163	0.070	4.253	0.339	0.1130
										(Sheet 2 of 3)

Table 4 (Concluded)										
Run	**Plant**	**Plant Height** ***H*****, ft**	**Plant Density** ***M*****, 1/ft²**	**Water Depth** Y_o**, ft**	**Mean Velocity** ***V*****, ft/s**	**Energy Slope** ***S***	**Average** ***n***	**Bed Hydraulic Radius ft**	**Bed** ***V*/V***	**Bed Manning's n**
II 9-3	Vally Elberberry	3.17	0.160	3.515	1.714	0.00267	0.068	3.434	0.317	0.1020
II 9-4	Vally Elberberry	3.17	0.160	2.999	2.038	0.00475	0.072	2.944	0.329	0.1030
II 10-1	Salt Cedar	5.00	0.058	4.692	1.364	0.00156	0.072	4.573	0.352	0.1190
II 10-2	Salt Cedar	5.00	0.058	4.522	1.902	0.00238	0.063	4.389	0.305	0.1020
II 10-3	Salt Cedar	5.00	0.058	3.660	2.350	0.00380	0.060	3.560	0.281	0.0910
II 10-4	Salt Cedar	5.00	0.058	3.062	2.246	0.00369	0.058	2.981	0.264	0.0830
II 10-5	Salt Cedar	5.00	0.058	2.768	2.462	0.00513	0.060	2.704	0.272	0.0840
II 10-6	Salt Cedar	5.00	0.058	2.714	3.067	0.00517	0.048	2.629	0.215	0.0660
II	Black Willow	4.00	0.213	4.646	1.028	0.00084		3.578	0.303	0.0980
II	Black Willow	4.00	0.213	4.677	1.809	0.00113		4.387	0.221	0.0740
II	Black Willow	4.00	0.213	4.554	2.503	0.00210		4.305	0.216	0.0720
II	Black Willow	4.00	0.213	2.232	2.257	0.00175		2.088	0.152	0.0450
II	Black Willow	4.00	0.213	2.974	2.984	0.00333		2.867	0.186	0.0580
II	Black Willow	4.00	0.213	2.693	2.590	0.00326		2.604	0.202	0.0620
II	Black Willow	4.00	0.213	2.547	2.381	0.00228		2.439	0.178	0.0540
II 13-1	Mountain Willow	5.00	0.450	2.226	2.061	0.00323	0.052	2.168	0.231	0.0690
II 13-2	Mountain Willow	5.00	0.450	1.986	2.309	0.00414	0.050	1.937	0.219	0.0640
II 13-3	Mountain Willow	5.00	0.450	2.451	2.137	0.00666	0.075	2.414	0.336	0.1020
II 13-4	Mountain Willow	5.00	0.450	2.683	1.999	0.00616	0.080	2.644	0.363	0.1120
II 13-5	Mountain Willow	5.00	0.450	3.063	2.000	0.00584	0.082	3.016	0.378	0.1190
II 13-6	Mountain Willow	5.00	0.450	3.582	1.710	0.00459	0.090	3.530	0.421	0.1360
II 13-7	Mountain Willow	5.00	0.450	4.104	1.462	0.00306	0.090	4.037	0.432	0.1430
II 13-8	Mountain Willow	5.00	0.450	4.351	1.465	0.00283	0.088	4.275	0.428	0.1420
II 13-9	Mountain Willow	5.00	0.450	4.639	1.725	0.00335	0.083	4.549	0.406	0.1370
II 13-10	Mountain Willow	5.00	0.450	4.194	1.967	0.00432	0.080	4.114	0.383	0.1270
II 13-11	Mountain Willow	5.00	0.450	4.534	2.936	0.00549	0.062	4.406	0.301	0.1010
II 14-1	Mt Willow w/o leaves	5.00	0.450	2.869	1.952	0.00379	0.066	2.809	0.299	0.0930
II 14-2	Mt Willow w/o leaves	5.00	0.450	4.515	1.207	0.00136	0.075	4.407	0.364	0.1220
										(Sheet 3 of 3)

Table 5
Summary of Large Flume Results with Mixed Plant Groupings (SI Units)

Run	Plants	Plant Density *M,* 1/m^2	Water Depth *Yo,* M	Mean Velocity *V,* m/sec	Energy Slope *S*	Average n	Hydraulic Radius R_h (bed), m	Shear Ratio V^*/V (bed)	Manning's n (bed)
2-1	20 Service Berry, 68 Yellow Twig Dogwood, 68 Euonymus	4.20	1.414	0.353	0.00084	0.062	1.366	0.300	0.101
2-2	20 Service Berry, 68 Yellow Twig Dogwood, 68 Euonymus	4.20	1.398	0.486	0.00122	0.054	1.343	0.259	0.087
2-3	20 Service Berry, 68 Yellow Twig Dogwood, 68 Euonymus	4.20	1.287	0.659	0.00219	0.052	1.238	0.248	0.082
2-4	20 Service Berry, 68 Yellow Twig Dogwood, 68 Euonymus	4.20	0.908	0.742	0.00398	0.055	0.883	0.249	0.078
2-5	20 Service Berry, 68 Yellow Twig Dogwood, 68 Euonymus	4.20	0.944	0.560	0.00253	0.059	0.919	0.270	0.085
2-6	20 Service Berry, 68 Yellow Twig Dogwood, 68 Euonymus	4.20	0.685	0.779	0.00551	0.055	0.670	0.244	0.073
3-1	68 Yellow Twig Dogwood, 68 Euonymus	3.66	1.410	0.360	0.00069	0.055	1.353	0.265	0.089
3-2	68 Yellow Twig Dogwood, 68 Euonymus	3.66	1.266	0.537	0.00125	0.048	1.209	0.228	0.075
3-3	68 Yellow Twig Dogwood, 68 Euonymus	3.66	0.728	0.638	0.00290	0.050	0.707	0.222	0.067
3-4	68 Yellow Twig Dogwood, 68 Euonymus	3.66	0.982	0.473	0.00126	0.050	0.946	0.228	0.072
7-1	22 Mulefat, 70 Alders	2.48	1.332	0.366	0.00107	0.066	1.293	0.318	0.106
7-2	22 Mulefat, 70 Alders	2.48	1.344	0.456	0.00102	0.052	1.288	0.249	0.083
7-3	22 Mulefat, 70 Alders	2.48	1.148	0.624	0.00173	0.047	1.099	0.219	0.071
7-4	22 Mulefat, 70 Alders	2.48	1.006	0.845	0.00395	0.050	0.972	0.230	0.073
8-1	22 Mulefat, 70 Alders, 66 Valley Elderberry	4.20	1.373	0.488	0.00228	0.073	1.341	0.355	0.119
8-2	22 Mulefat, 70 Alders, 66 Valley Elderberry	4.20	1.340	0.572	0.00292	0.070	1.308	0.338	0.113
8-3	22 Mulefat, 70 Alders, 66 Valley Elderberry	4.20	1.377	0.751	0.00427	0.065	1.340	0.316	0.106
8-4	22 Mulefat, 70 Alders, 66 Valley Elderberry	4.20	1.189	0.533	0.00315	0.075	1.164	0.354	0.116
8-5	22 Mulefat, 70 Alders, 66 Valley Elderberry	4.20	1.113	0.567	0.00372	0.075	1.091	0.352	0.114
8-6	22 Mulefat, 70 Alders, 66 Valley Elderberry	4.20	1.166	0.678	0.00390	0.065	1.137	0.306	0.100
11-1	23 Salt Cedar, 83 Black Willows, 50 Red Willows	4.20	1.433	0.658	0.00290	0.062	1.390	0.302	0.102
11-2	23 Salt Cedar, 83 Black Willows, 50 Red Willows	4.20	1.320	0.794	0.00445	0.062	1.283	0.297	0.099
11-3	23 Salt Cedar, 83 Black Willows, 50 Red Willows	4.20	1.437	0.401	0.00158	0.075	1.403	0.367	0.124
11-4	23 Salt Cedar, 83 Black Willows, 50 Red Willows	4.20	0.955	0.528	0.00314	0.070	0.935	0.323	0.102
11-5	23 Salt Cedar, 83 Black Willows, 50 Red Willows	4.20	0.787	0.646	0.00471	0.065	0.772	0.291	0.089
11-6	23 Salt Cedar, 83 Black Willows, 50 Red Willows	4.20	0.814	0.959	0.00834	0.059	0.796	0.267	0.082
11-7	23 Salt Cedar, 83 Black Willows, 50 Red Willows	4.20	0.665	0.726	0.00456	0.053	0.649	0.236	0.070
12-1	83 Black Willows, 50 Red Willows	3.58	1.416	0.354	0.00079	0.060	1.366	0.291	0.098

(Continued)

Table 5 (Concluded)									
Run	**Plants**	**Plant Density** ***M*****, 1/m²**	**Water Depth** Y_o**, m**	**Mean Velocity** ***V*****, m/sec**	**Energy Slope** ***S***	**Average n**	**Hydraulic Radius** R_h **(bed), m**	**Shear Ratio** ***V*/V*** **(bed)**	**Manning's n (bed)**
12-2	83 Black Willows, 50 Red Willows	3.58	1.426	0.551	0.00113	0.046	1.353	0.220	0.074
12-3	83 Black Willows, 50 Red Willows	3.58	1.388	0.763	0.00210	0.045	1.320	0.215	0.072
12-4	83 Black Willows, 50 Red Willows	3.58	0.906	0.910	0.00333	0.041	0.867	0.186	0.058
12-5	83 Black Willows, 50 Red Willows	3.58	0.821	0.789	0.00326	0.045	0.791	0.202	0.062
12-6	83 Black Willows, 50 Red Willows	3.58	0.776	0.726	0.00228	0.040	0.743	0.178	0.054
12-7	83 Black Willows, 50 Red Willows	3.58	0.680	0.688	0.00175	0.035	0.647	0.151	0.045

Table 6
Summary of Large Flume Results with Mixed Plant Groupings (Non-SI Units)

Run	Plants	Plant Density *M*, 1/ft^2	Water Depth *Yo*, ft	Mean Velocity *V*, ft/s	Energy Slope *S*	Average n	Hydraulic Radius R_h (bed), ft	Shear Ratio *V*/V* (bed)	Manning's n (bed)
2-1	20 Service Berry, 68 Yellow Twig Dogwood, 68 Euonymus	0.39	4.638	1.159	0.00084	0.062	4.483	0.300	0.101
2-2	20 Service Berry, 68 Yellow Twig Dogwood, 68 Euonymus	0.39	4.588	1.594	0.00122	0.054	4.407	0.259	0.087
2-3	20 Service Berry, 68 Yellow Twig Dogwood, 68 Euonymus	0.39	4.222	2.161	0.00219	0.052	4.061	0.248	0.082
2-4	20 Service Berry, 68 Yellow Twig Dogwood, 68 Euonymus	0.39	2.979	2.434	0.00398	0.055	2.896	0.249	0.078
2-5	20 Service Berry, 68 Yellow Twig Dogwood, 68 Euonymus	0.39	3.096	1.837	0.00253	0.059	3.014	0.270	0.085
2-6	20 Service Berry, 68 Yellow Twig Dogwood, 68 Euonymus	0.39	2.249	2.557	0.00551	0.055	2.197	0.244	0.073
3-1	68 Yellow Twig Dogwood, 68 Euonymus	0.34	4.627	1.181	0.00069	0.055	4.439	0.265	0.089
3-2	68 Yellow Twig Dogwood, 68 Euonymus	0.34	4.152	1.761	0.00125	0.048	3.966	0.228	0.075
3-3	68 Yellow Twig Dogwood, 68 Euonymus	0.34	2.388	2.094	0.00290	0.050	2.319	0.222	0.067
3-4	68 Yellow Twig Dogwood, 68 Euonymus	0.34	3.222	1.552	0.00126	0.050	3.103	0.228	0.072
7-1	22 Mulefat, 70 Alders	0.23	4.370	1.201	0.00107	0.066	4.243	0.318	0.106
7-2	22 Mulefat, 70 Alders	0.23	4.411	1.496	0.00102	0.052	4.227	0.249	0.083
7-3	22 Mulefat, 70 Alders	0.23	3.766	2.048	0.00173	0.047	3.605	0.219	0.071
7-4	22 Mulefat, 70 Alders	0.23	3.301	2.772	0.00395	0.050	3.189	0.230	0.073
8-1	22 Mulefat, 70 Alders, 66 Valley Elderberry	0.39	4.506	1.601	0.00228	0.073	4.399	0.355	0.119
8-2	22 Mulefat, 70 Alders, 66 Valley Elderberry	0.39	4.397	1.876	0.00292	0.070	4.290	0.338	0.113
8-3	22 Mulefat, 70 Alders, 66 Valley Elderberry	0.39	4.517	2.463	0.00427	0.065	4.396	0.316	0.106
8-4	22 Mulefat, 70 Alders, 66 Valley Elderberry	0.39	3.901	1.750	0.00315	0.075	3.820	0.354	0.116
8-5	22 Mulefat, 70 Alders, 66 Valley Elderberry	0.39	3.650	1.860	0.00372	0.075	3.578	0.352	0.114
8-6	22 Mulefat, 70 Alders, 66 Valley Elderberry	0.39	3.826	2.225	0.00390	0.065	3.731	0.306	0.100
11-1	23 Salt Cedar, 83 Black Willows, 50 Red Willows	0.39	4.702	2.159	0.00290	0.062	4.560	0.302	0.102
11-2	23 Salt Cedar, 83 Black Willows, 50 Red Willows	0.39	4.330	2.604	0.00445	0.062	4.209	0.297	0.099
11-3	23 Salt Cedar, 83 Black Willows, 50 Red Willows	0.39	4.716	1.317	0.00158	0.075	4.602	0.367	0.124
11-4	23 Salt Cedar, 83 Black Willows, 50 Red Willows	0.39	3.133	1.731	0.00314	0.070	3.069	0.323	0.102
11-5	23 Salt Cedar, 83 Black Willows, 50 Red Willows	0.39	2.583	2.120	0.00471	0.065	2.532	0.291	0.089
11-6	23 Salt Cedar, 83 Black Willows, 50 Red Willows	0.39	2.669	3.147	0.00834	0.059	2.610	0.267	0.082
11-7	23 Salt Cedar, 83 Black Willows, 50 Red Willows	0.39	2.182	2.383	0.00456	0.053	2.130	0.236	0.070
12-1	83 Black Willows, 50 Red Willows	0.333	4.646	1.162	0.00079	0.060	4.482	0.291	0.098

(Continued)

Table 6 (Concluded)									
Run	**Plants**	**Plant Density** ***M*, 1/ft^2**	**Water Depth** **Y_o, ft**	**Mean Velocity** ***V*, ft/s**	**Energy Slope *S***	**Average n**	**Hydraulic Radius R_h (bed), ft**	**Shear Ratio** ***V*/V*** **(bed)**	**Manning's n (bed)**
12-2	83 Black Willows, 50 Red Willows	0.333	4.677	1.809	0.00113	0.046	4.440	0.220	0.074
12-3	83 Black Willows, 50 Red Willows	0.333	4.554	2.503	0.00210	0.045	4.330	0.215	0.072
12-4	83 Black Willows, 50 Red Willows	0.333	2.974	2.984	0.00333	0.041	2.845	0.186	0.058
12-5	83 Black Willows, 50 Red Willows	0.333	2.693	2.590	0.00326	0.045	2.596	0.202	0.062
12-6	83 Black Willows, 50 Red Willows	0.333	2.547	2.381	0.00228	0.040	2.438	0.178	0.054
12-7	83 Black Willows, 50 Red Willows	0.333	2.232	2.257	0.00175	0.035	2.123	0.151	0.045

Table 7
Small Flume Results, Drag Measurements

		With Leaves				Without Leaves			
		Approach Velocity		Drag Force		Approach Velocity		Drag Force	
Run	Plant	ft/sec	m/sec	lbf	N	ft/sec	m/sec	lbf	N
1	Staghorn Sumac	1.63	0.50	0.216	0.961	1.63	0.50	0.052	0.231
2	Staghorn Sumac	2.15	0.66	0.310	1.379	2.01	0.61	0.095	0.423
3	Staghorn Sumac	2.62	0.80	0.362	1.610	2.12	0.65	0.108	0.480
4	Staghorn Sumac	2.70	0.82	0.388	1.726	2.51	0.77	0.172	0.765
5	Staghorn Sumac	2.84	0.87	0.414	1.842	3.06	0.93	0.216	0.961
6	Staghorn Sumac	3.37	1.03	0.431	1.917	3.34	1.02	0.237	1.054
7	Staghorn Sumac	3.64	1.11	0.466	2.073	3.48	1.06	0.280	1.245
8	Staghorn Sumac	4.17	1.27	0.569	2.531	3.92	1.19	0.401	1.784
9	Staghorn Sumac	4.31	1.31	0.603	2.682	4.44	1.35	0.474	2.108
10	Staghorn Sumac	4.44	1.35	0.638	2.838	4.80	1.46	0.526	2.340
1	Artic Blue Willow	1.02	0.31	0.207	0.921	1.43	0.44	0.129	0.574
2	Artic Blue Willow	1.32	0.40	0.289	1.286	1.82	0.55	0.155	0.689
3	Artic Blue Willow	1.79	0.55	0.366	1.628	2.46	0.75	0.207	0.921
4	Artic Blue Willow	2.15	0.66	0.431	1.917	2.95	0.90	0.224	0.996
5	Artic Blue Willow	2.34	0.71	0.483	2.148	3.50	1.07	0.272	1.210
6	Artic Blue Willow	2.73	0.83	0.526	2.340	4.25	1.30	0.345	1.535
7	Artic Blue Willow	2.92	0.89	0.560	2.491	4.66	1.42	0.397	1.766
8	Artic Blue Willow	2.98	0.91	0.578	2.571	4.77	1.45	0.440	1.957
9	Artic Blue Willow	3.48	1.06	0.733	3.261	4.94	1.51	0.466	2.073
10	Artic Blue Willow	4.39	1.34	0.922	4.101	5.19	1.58	0.517	2.300
1	Norway Maple	0.94	0.29	0.089	0.396	1.27	0.39	0.036	0.160
2	Norway Maple	1.21	0.37	0.125	0.556	1.93	0.59	0.058	0.258
3	Norway Maple	1.71	0.52	0.201	0.894	2.40	0.73	0.085	0.378
4	Norway Maple	2.23	0.68	0.241	1.072	2.92	0.89	0.134	0.596
5	Norway Maple	3.01	0.92	0.304	1.352	3.61	1.10	0.179	0.796
6	Norway Maple	3.56	1.09	0.371	1.650	4.17	1.27	0.210	0.934
7	Norway Maple	3.89	1.19	0.464	2.064	4.31	1.31	0.299	1.330
8	Norway Maple	4.08	1.24	0.589	2.620	4.44	1.35	0.321	1.428
9	Norway Maple	4.31	1.31	0.652	2.900	4.61	1.41	0.357	1.588
10	Norway Maple	4.53	1.38	0.741	3.296		0.00		0.000
1	Western Sand Cherry	1.10	0.34	0.071	0.316	1.43	0.44	0.031	0.138
2	Western Sand Cherry	1.68	0.51	0.107	0.476	2.01	0.61	0.071	0.316
3	Western Sand Cherry	2.12	0.65	0.143	0.636	2.54	0.77	0.098	0.436
4	Western Sand Cherry	2.51	0.77	0.170	0.756	2.79	0.85	0.125	0.556
5	Western Sand Cherry	2.81	0.86	0.205	0.912	3.17	0.97	0.161	0.716
6	Western Sand Cherry	3.20	0.98	0.250	1.112	3.50	1.07	0.174	0.774
7	Western Sand Cherry	3.39	1.03	0.308	1.370	3.84	1.17	0.196	0.872
8	Western Sand Cherry	3.64	1.11	0.348	1.548	4.00	1.22	0.223	0.992
9	Western Sand Cherry	3.75	1.14	0.384	1.708	4.17	1.27	0.254	1.130
10	Western Sand Cherry	3.89	1.19	0.420	1.868	4.53	1.38	0.348	1.548
1	Common Privet	1.13	0.34	0.198	0.881	1.32	0.40	0.075	0.334
2	Common Privet	1.71	0.52	0.472	2.100	2.10	0.64	0.302	1.343
3	Common Privet	2.18	0.66	0.731	3.252	2.57	0.78	0.377	1.677
4	Common Privet	2.90	0.88	0.811	3.607	2.73	0.83	0.396	1.761
5	Common Privet	3.34	1.02	0.972	4.324	3.23	0.98	0.708	3.149
6	Common Privet	3.59	1.09	1.274	5.667	3.42	1.04	0.797	3.545
7	Common Privet	3.75	1.14	1.585	7.050	3.73	1.14	0.943	4.195
8	Common Privet	4.11	1.25	1.896	8.434	4.03	1.23	1.085	4.826
9	Common Privet	4.39	1.34	2.132	9.484	4.17	1.27	1.189	5.289
10	Common Privet	4.44	1.35	2.179	9.693	4.66	1.42	1.302	5.792
1	Blue Elberberry	1.21	0.37	0.269	1.197	1.27	0.39	0.113	0.503
2	Blue Elberberry	1.68	0.51	0.491	2.184	1.57	0.48	0.170	0.756
3	Blue Elberberry	1.96	0.60	0.745	3.314	1.99	0.61	0.212	0.943
4	Blue Elberberry	2.46	0.75	1.415	6.294	2.18	0.66	0.259	1.152
5	Blue Elberberry	2.76	0.84	1.745	7.762	2.73	0.83	0.410	1.824
6	Blue Elberberry	2.98	0.91	2.052	9.128	3.31	1.01	0.552	2.455

(Continued)

Table 7 (Concluded)

Run	Plant	With Leaves				Without Leaves			
		Approach Velocity		Drag Force		Approach Velocity		Drag Force	
		ft/sec	m/sec	lbf	N	ft/sec	m/sec	lbf	N
7	Blue Elberberry	3.39	1.03	2.406	10.702	3.61	1.10	0.717	3.189
8	Blue Elberberry	3.89	1.19	2.783	12.379	4.06	1.24	1.024	4.555
9	Blue Elberberry	4.25	1.30	3.349	14.897	5.11	1.56	1.434	6.379
10	Blue Elberberry		0.00		0.000	5.33	1.62	1.991	8.856
1	French Pink Pussywillow	1.35	0.41	0.192	0.854	1.41	0.43	0.192	0.854
2	French Pink Pussywillow	1.99	0.61	0.625	2.780	1.54	0.47	0.288	1.281
3	French Pink Pussywillow	2.26	0.69	0.673	2.994	2.32	0.71	0.375	1.668
4	French Pink Pussywillow	2.57	0.78	0.827	3.679	2.40	0.73	0.452	2.011
5	French Pink Pussywillow	2.84	0.87	1.106	4.920	2.51	0.77	0.529	2.353
6	French Pink Pussywillow	3.34	1.02	1.346	5.987	2.90	0.88	0.837	3.723
7	French Pink Pussywillow	3.61	1.10	1.827	8.127	3.34	1.02	1.010	4.493
1	Sycamore	1.21	0.37	0.144	0.641	1.35	0.41	0.058	0.258
2	Sycamore	1.63	0.50	0.264	1.174	1.90	0.58	0.096	0.427
3	Sycamore	1.93	0.59	0.341	1.517	2.07	0.63	0.135	0.601
4	Sycamore	2.65	0.81	0.538	2.393	2.51	0.77	0.183	0.814
5	Sycamore	3.12	0.95	0.740	3.292	2.79	0.85	0.231	1.028
6	Sycamore	3.20	0.98	0.817	3.634	3.06	0.93	0.245	1.090
7	Sycamore	3.59	1.09	0.952	4.235	3.23	0.98	0.274	1.219
8	Sycamore	3.78	1.15	1.096	4.875	3.70	1.13	0.452	2.011
9	Sycamore	4.55	1.39	1.442	6.414	3.81	1.16	0.529	2.353
10	Sycamore	4.66	1.42	1.490	6.628	3.89	1.19	0.553	2.460
1	Yellow Twig Dogwood type 1	1.68	0.51	0.108	0.480	1.41	0.43	0.108	0.480
2	Yellow Twig Dogwood type 1	2.01	0.61	0.162	0.721	2.04	0.62	0.206	0.916
3	Yellow Twig Dogwood type 1	2.18	0.66	0.201	0.894	2.51	0.77	0.294	1.308
4	Yellow Twig Dogwood type 1	2.62	0.80	0.245	1.090	3.31	1.01	0.412	1.833
5	Yellow Twig Dogwood type 1	3.26	0.99	0.392	1.744	3.61	1.10	0.451	2.006
6	Yellow Twig Dogwood type 1	3.53	1.08	0.480	2.135	3.92	1.19	0.451	2.006
7	Yellow Twig Dogwood type 1	4.22	1.29	0.593	2.638	4.44	1.35	0.623	2.771
8	Yellow Twig Dogwood type 1	4.44	1.35	0.618	2.749	4.50	1.37	0.627	2.789
9	Yellow Twig Dogwood type 1	4.55	1.39	0.647	2.878	4.55	1.39	0.657	2.922
10	Yellow Twig Dogwood type 1	4.53	1.38	0.642	2.856	4.75	1.45	0.588	2.616
1	Yellow Twig Dogwood type 2	1.05	0.32	0.088	0.391	1.27	0.39	0.059	0.262
2	Yellow Twig Dogwood type 2	1.46	0.45	0.127	0.565	1.65	0.50	0.103	0.458
3	Yellow Twig Dogwood type 2	1.79	0.55	0.186	0.827	2.04	0.62	0.162	0.721
4	Yellow Twig Dogwood type 2	2.59	0.79	0.284	1.263	2.79	0.85	0.255	1.134
5	Yellow Twig Dogwood type 2	2.95	0.90	0.343	1.526	3.06	0.93	0.294	1.308
6	Yellow Twig Dogwood type 2	3.50	1.07	0.431	1.917	3.84	1.17	0.348	1.548
7	Yellow Twig Dogwood type 2	3.89	1.19	0.471	2.095	3.84	1.17	0.348	1.548
8	Yellow Twig Dogwood type 2	4.42	1.35	0.529	2.353	4.17	1.27	0.373	1.659
9	Yellow Twig Dogwood type 2	4.50	1.37	0.534	2.375	4.33	1.32	0.392	1.744
10	Yellow Twig Dogwood type 2	4.55	1.39	0.539	2.398	4.50	1.37	0.422	1.877
1	Euonymus	1.13	0.34	0.093	0.414	0.94	0.29	0.074	0.329
2	Euonymus	1.52	0.46	0.176	0.783	1.46	0.45	0.098	0.436
3	Euonymus	2.48	0.76	0.324	1.441	1.77	0.54	0.167	0.743
4	Euonymus	2.84	0.87	0.353	1.570	2.18	0.66	0.225	1.001
5	Euonymus	3.31	1.01	0.500	2.224	2.87	0.87	0.363	1.615
6	Euonymus	3.78	1.15	0.500	2.224	3.23	0.98	0.436	1.939
7	Euonymus	3.84	1.17	0.510	2.269	3.73	1.14	0.490	2.180
8	Euonymus	4.39	1.34	0.539	2.398	4.28	1.30	0.534	2.375
9	Euonymus	4.47	1.36	0.564	2.509	4.44	1.35	0.539	2.398
10	Euonymus	4.69	1.43	0.588	2.616		0.00		0.000
1	Yellow Twig Dogwood type 3	1.57	0.48	0.196	0.872	2.15	0.66	0.157	0.698
2	Yellow Twig Dogwood type 3	2.29	0.70	0.314	1.397	2.46	0.75	0.206	0.916
3	Yellow Twig Dogwood type 3	2.43	0.74	0.343	1.526	2.90	0.88	0.255	1.134
4	Yellow Twig Dogwood type 3	2.70	0.82	0.373	1.659	3.45	1.05	0.275	1.223
5	Yellow Twig Dogwood type 3	2.95	0.90	0.436	1.939	4.28	1.30	0.284	1.263
6	Yellow Twig Dogwood type 3	3.50	1.07	0.480	2.135				
7	Yellow Twig Dogwood type 3	4.22	1.29	0.500	2.224				

Table 8
Large Flume Results, Drag Measurements

		With Leaves			
		Approach Velocity		Drag Force	
Run	Plant	ft/sec	m/sec	lbf	N
6-2:1	Mulefat	1.10	0.34	0.083	0.369
6-2:2	Mulefat	1.50	0.46	0.130	0.578
6-2:3	Mulefat	1.70	0.52	0.172	0.765
6-2:4	Mulefat	2.40	0.73	0.232	1.032
6-2:5	Mulefat	2.70	0.82	0.362	1.610
6-2:6	Mulefat	3.10	0.94	0.426	1.895
7-1:1	Alder	0.43	0.13	0.040	0.178
7-1:2	Alder	0.88	0.27	0.109	0.485
7-1:3	Alder	1.10	0.34	0.234	1.041
7-1:4	Alder	1.60	0.49	0.404	1.797
8-1:1	Valley Elderberry	0.40	0.12	0.294	1.308
8-1:2	Valley Elderberry	0.50	0.15	0.438	1.948
8-1:3	Valley Elderberry	0.60	0.18	0.574	2.553
8-1:4	Valley Elderberry	0.70	0.21	0.745	3.314
8-1:5	Valley Elderberry	0.80	0.24	0.989	4.399
8-1:6	Valley Elderberry	1.10	0.34	1.277	5.680
8-1:7	Valley Elderberry	1.40	0.43	1.404	6.245
11-1:1	Black Willow	0.85	0.26	0.110	0.489
11-1:2	Black Willow	1.00	0.30	0.170	0.756
11-1:3	Black Willow	1.10	0.34	0.210	0.934
11-1:4	Black Willow	1.30	0.40	0.320	1.423
11-1:5	Black Willow	1.50	0.46	0.470	2.091
11-1:6	Black Willow	1.65	0.50	0.510	2.269
11-1:7	Black Willow	1.70	0.52	0.680	3.025
11-1:8	Black Willow	1.90	0.58	0.770	3.425
11-1:9	Black Willow	2.10	0.64	0.960	4.270
11-1:10	Black Willow	2.30	0.70	1.230	5.471

Table 9
Modulus of Plant Stiffness for Evaluated Plants

Plant name		$E_S/(H/D_S)^{1.5}$ N/m²	$E_S/(H/D_S)^{1.5}$ lbf/ft²
Alder	*Alnus incana*	1.804e+06	3.768e+04
Arctic Blue Willow	*Salix purpurea nana*	4.091e+05	8.544e+03
Black Willow	*Salix nigra*	2.930e+05	6.119e+03
Blue Elderberry	*Sambucus Canadensis*	2.733e+05	5.708e+03
Common Privet	*Ligustrum vulgare*	7.7040e+05	1.609e+04
Yellow Twig Dogwood	*Cornus stolonifera flaviramea*	2.550e+06	5.326e+04
Red-osier Dogwood	*Cornus Sericea*	4.342e+06	9.069e+04
Berried Elderberry	*Sambucus racemosa*	8.168e+04	1.706e+03
Purpleleaf Euonymus	*Euonymus fortunei colorata*	2.278e+06	4.758e+04
Mountain Black Willow	*Salix monticola*	7.430e+05	1.552e+04
Mulefat	*Baccharis glutinosa*	8.992e+05	1.878e+04
Norway Maple	*Acer platenoides*	4.569e+06	9.542e+04
French Pink Pussywillow	*Salix caprea pendula*	3.345e+05	6.986e+03
Red Willow	*Salix spp.*	8.810e+05	1.840e+04
Salt Cedar	*Tamarix spp.*	3.930e+06	8.207e+04
Service Berry	*Amelanchier*	4.003e+06	8.360e+04
Staghorn Sumac	*Rhus typhina*	1.095e+06	2.288e+04
Sycamore	*Platenus acer ifolia*	3.244e+06	6.774e+04
Valley Elderberry	*Sambucus mexicana*	7.672e+06	1.602e+05
Western Sand Cherry	*Prunis besseyi*	3.567e+06	7.449e+04
Sand Bar Willow	*Salix exigua*	4.990e+06	1.040e+05
Pacific Willow	*Salix lasiandra*	5.300e+06	1.120e+05
Lemon's Willow	Salix lemonii	4.090e+06	8.530e+04
Wild Rose Bush	Rosa spp.	6.070e+06	1.250e+05

Appendix A
Example Problem

The equations developed in this report allow hydraulic roughness values to be determined for homogenous and nonhomogeneous flood plains. When a number of species are present in the floodplain or area of interest, the values for the various plants are either combined, as shown in Equation 29, or the flood plain is broken into homogenous areas that are then either solved simultaneously for the flow or aggregated to provide a representative roughness (i.e., Manning's n) value.

The following is an example for determining the vegetative resistance and the equivalent resistance of the left bank of a floodplain. The left bank is divided into three subareas with the far left area vegetated with shrubs, the middle area vegetated with three different plant types, and the right subarea vegetated with willows as shown in Figure A1. For a given flow depth in the main channel, Table A1 shows the flow depth, area, wetted perimeter, and hydraulic radius for each subarea. The slope of each area is 0.0002, the fluid density is 1,000 kg/m^3, and the kinematic viscosity is 1.3E+06 m^2/s. The properties of the channel are summarized in Table A1 for ease of reference.

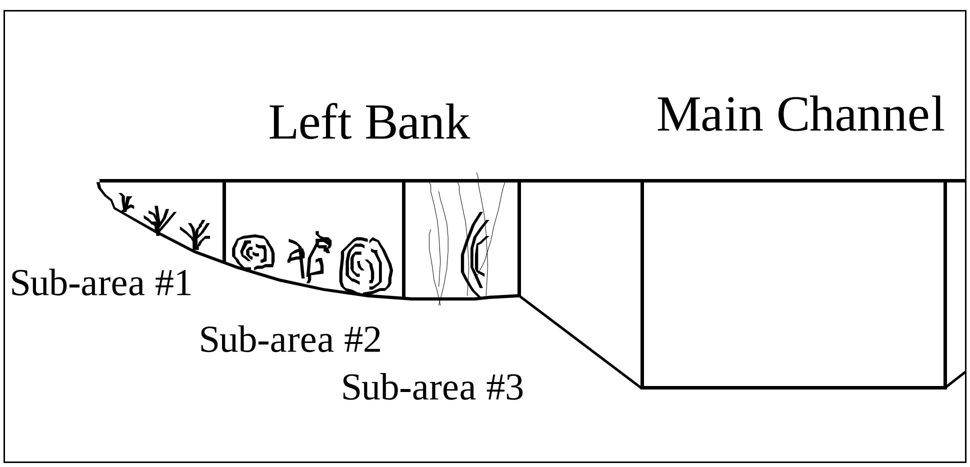

Figure A1. Left bank floodplain for example problem showing calculation subareas based on vegetation types

Table A1
Channel Properties for Example Problem

Channel Properties	Subarea 1	Subarea 2	Subarea 3	Overbank Total
S	0.0002	0.0002	0.0002	.0002
Y_o m	0.61	1.524	2.134	
Flow Area m^2	27.87	46.45	32.52	106.84
P m	31.39	31.09	15.85	78.33
R_h m	0.89	1.49	2.05	1.364

Table A2 lists the plant characteristics and properties for the shrubs in subareas 1 through 3. The stiffness modulus was measured in the field by applying Equation 33 for subarea 1, by using Equation 35 for weighted plant characteristic values for subarea 2, and by using the value for Pacific willows from Table 9 for subarea 3 multiplied by the $(H/D_s)^{1.5}$ value for the willows in subarea 3. The use of the value from Table 9 and the H/D parameter for the willows in subarea 3 provides an estimate of the actual E_s for the willows in the subarea that are different in size from those evaluated in the compilation of the data presented in Table 9.

Table A2 also lists the plant characteristics and shows the calculations to determine the weighted average characteristics to be used for the resistance calculations. This is done by multiplying the various plant characteristics by that plant's relative density on the floodplain in decimal form, H_1M_1/M_{total}, where the subscript 1 refers to plant type 1. These values are then summed for all three plant types to arrive at the weighted value for H. Thus, the equation for the weighted value becomes as follows:

$$H_{ave} = H_1 \frac{M_1}{M_{total}} + H_2 \frac{M_2}{M_{total}} + H_3 \frac{M_2}{M_{total}}$$

This averaging technique was verified using flume data from the Utah Water Research Laboratory Study and provides the correct average values for use in the equations presented herein.

Equation 23 was used to calculate V_*/V for the partially submerged vegetation in subarea 1 while Equation 21 was used for the fully submerged subareas 2 and 3. Manning's n values were calculated in the same way using Equation 24 for subarea 1 and Equation 22 for subareas 2 and 3.

The calculated Manning's n values for subareas 1 through 3 are 0.075, 0.088, and 0.127, respectively, while the V_*/V values are 0.240, 0.257, and 0.353, respectively. The values for the various subareas can then be used individually in a hydraulic model or composited to obtain a value for the entire channel. Methods described in the SAM User's Manual (Thomas et al. in preparation)[1] are recommended for compositing the subareas if that is necessary.

[1] References in this appendix are cited in the References section at the end of the main text.

Table A2
Plant Characteristics and Roughness Calculations for Subareas 1-3

Plant Characteristics	Sub area 1	Subarea 2 Plant Type 1	Subarea 2 Plant Type 2	Subarea 2 Plant Type 3	Subarea 2 Weighted Values	Subarea 3 (Pacific Willow)
H m	0.91	0.2	0.71	0.99	0.59	1.83
H' m	0.76	0.2	0.51	0.81	0.49	1.52
We m	0.76	0.254	0.18	0.86	0.48	1.22
No. of Stems	4	2	6	1	2.20	4
D_s cm	1.27	0.64	0.64	1.2	0.86	1.3
A_s m^2 π $D_s^2 / 4$ x (no. of stems)	5.06E-04	6.43E-05	1.93E-04	1.13E-04	1.03E-04	5.31E-04
M (plants / m^2)	0.52	1.83	0.61	1.62	4.06	0.11
M / M total (%)		45.0	15.0	39.9	100.0	
H/D_s	72	31	111	82	64	141
F_{45}, N	8.08					
Es, N/m^2, Eq 33	1.75E+09					
Es, N/m^2, Eq 35	1.33E+09	3.15E+08	3.59E+09	1.49E+09	1.28E+09	6.56E+09
Es, N/m^2, Table 9 x $(H/D_s)^{1.5}$						8.85E+09
Vegetative Resistance						
Y_o / H	0.67				2.72	1.17
Submergence P ≤ 0.8H ≤ Full	Partial				Full	Full
A_i or A_i* (m^2)	0.35				0.24	1.85
$V_* = (gR_hS)^{1/2}$	4.18E-02				5.41E-02	6.34E-02
Es As / $\rho A_i V_*^2$	1449447				207582	630112
M A_i*	0.182				0.964	0.204
$V_* R_h / \nu$	28608				61971	100009
V_*/V (Eq 23)	.130					
V_*/V (Eq 21)					0.380	0.350
Manning's n (Eq 22 or 24)	0.075 (Eq 24)				0.130 (Eq 22)	0.126

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14. ABSTRACT

Flume studies were conducted to determine hydraulic resistance of flexible plants that deform with turbulent flow. Both partially submerged and fully submerged plants were studied. The flexible stems and varying shapes of a plant leaf mass greatly complicate the understanding of resistance. The deformation of plant shape with flow precludes the use of constant blockage or plant density in predicting resistance. This study considers the effects on channel resistance for the variables of plant type, plant geometry, plant density, plant flexibility, and submerged and partially submerged plants. Regression equations were developed for determining the Manning's roughness coefficient.

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