Determining Drag Coefficients and Area for Vegetation

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Complexity	Analytical Value	Cost
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Low Moderate	Low Moderate	Low Moderate

OVERVIEW

The technical note (TN) "Resistance Due to Vegetation" (Ecosystem Management and Restoraton Research Program (EMRRP) TN SR-7) presents equations for the evaluation of Manning's resistance coefficient in floodways occupied by vegetation. These equations require an estimate of the drag coefficient and area for the vegetation. This technical note presents a means to make these estimates.

PLANNING

Application of the equations in the accompanying technical note "Resistance Due to Vegetation" requires the measurement or estimation of values for the characteristic area of the vegetation A_v and of a bulk drag coefficient C_d.

The characteristic area of the vegetation and the bulk drag coefficient must be considered together. Dimensional analysis can be used to develop an empirical formula for drag:

$$D = \frac{1}{2} r A U^2 \left(\frac{lU}{u} \right)^a \qquad (1)$$

The term in parentheses is the Reynolds number (R_e), which, along with its exponent a, is replaced by the drag coefficient C_d in the more conventional form of this equation:

$$D = \frac{1}{2} r\, C_d A U^2 \qquad (2)$$

Thus, the drag coefficient is only a function of the R_e, and equality of R_e for geometrically similar objects implies equality of the drag coefficients. This important statement is the basis for later comparisons between data obtained for flows of different fluid mediums (air and water).

Including a representative reference area A in Equation 2 presents some difficulty for vegetation. The drag coefficient calculated from measured drag data depends on how A is defined. The frontal area of the object projected on a plane normal to the flow is the most common reference area. Others include the wetted area, the plan form area, and the two-thirds power of volume. An area reference is often selected arbitrarily but can significantly influence the calculated drag coefficient. Table 1 shows the variation of drag coefficient with reference area for three simple objects. The drag is normalized to that calculated for frontal area.

Vogel (1984) suggested that frontal area is most appropriate for streamlined objects at high R_e values when drag is essentially the dynamic pressure times the frontal area of the object. Wetted area is most relevant for streamlined objects for which the drag is due to viscosity and shear; plan area is preferred for objects with significant lift, such as airfoils; and the two-thirds volume would be appropriate for objects with lift proportional to volume, such as airships. The conventional application of each of these areas is to solid objects whereas vegetation is porous.

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Table 1. Normalized Drag Coefficients for Differing Reference Areas

	Sphere	*Cylinder*	*4:1 Ellipsoid*
Frontal Area	1.0	1.0	1.0
Plan Form Area	1.0	1.0	0.25
Wetted Area	0.25	0.318	0.078
Volume$^{2/3}$	1.208	0.932	0.480

Vegetation does not generally experience lift as a consequence of fluid flow, so the plan area and two-thirds volume measures can be dismissed on the basis of physical considerations. The other two measures make physical sense but both present practical limitations. Measuring the entire wetted area of the vegetation in a floodplain is clearly impractical. Methods of defining the frontal area of a dense stand of riparian vegetation are not apparent. Projecting the frontal area in the conventional form (i.e., as a solid object) would result in complete blockage of the flow area occupied by the vegetation. Thus, determining the best approach for dealing with permeable objects like vegetation using techniques normally applied to solid objects is not straight-forward.

Many researchers have used the leaf area index (LAI) in place of A for modeling wind flow through and over vegetation. The LAI is equivalent to the vegetation area based on frontal density A_d and to the vegetation density (Veg_d) defined in Equation 5 times a unit volume. An obvious problem with using these measures in Equation 2 is that the units are not consistent; A is in units L^2 whereas LAI and A_d have units 1/L. The drag is not a dimensionless value when LAI or A_d is substituted for A in Equation 2, but rather is the drag per unit volume of fluid. This measure of drag is ideal for evaluating momentum loss over a control volume. If the effective area is the area over which the drag is exerted, then LAI and A_d make physical sense as well. Dudley (1997) presents a reasonable approach for measuring A_d in the field using an inclined point frame.

Henceforth, the reference area for the vegetation will be specified and the associated drag coefficient denoted by subscript; f is used for frontal area; w is used for wetted area; and d is used for vegetation density. The Rahmeyer data were used to calculate the drag coefficient using the three different reference areas. Though every effort was made to compute all three, the data were not sufficient to do so in some cases.

Few data are available from which drag coefficients can be computed for vegetation immersed in flowing water. Rahmeyer et al. (1995) present what is probably the most complete data set on the subject. These investigators devised a technique for measuring drag on live vegetation in laboratory flumes using a load cell and strain gauge. Various combinations, sizes, and densities of 20 species of vegetation were evaluated for several flow conditions. Tables 2 and 3 summarize the measured data and calculated drag coefficient. Though extensive measurements of the vegetation were recorded, a density measure such as Veg_d or LAI was not recorded. The C_{dd} values reported herein were estimated from plant characteristics.

Additional data are available for drag coefficients and areas of vegetation (see Appendix). The drag coefficients derived from wind tunnel or field data for air are equivalent to drag coefficients for water provided the R_e values are equal and the vegetation is geometrically similar. Unfortunately, R_e and reference areas are seldom recorded with published data; therefore the utility of drag coefficients presented in the literature is limited.

For deciduous vegetation, both the area and the drag coefficient will vary depending on the condition of the vegetation (leaf on versus leaf off). Table 3 presents examples of how these values vary for some vegetation species.

Table 2. Summary of Large Flume Data (after Rahmeyer et al. (1995))

Plant	A_f (ft^2)	Vel (fps)	Drag (lbs)	C_{df}	C_dA_f
Dogwood	0.8125	1.1	0.250	0.2630	0.2137
	0.8125	2.0	0.300	0.0955	0.0776
	0.8125	2.7	0.375	0.0655	0.0532
	0.8125	1.8	0.375	0.1473	0.1197
	0.8125	1.8	0.375	0.1473	0.1197
	0.8125	2.7	0.500	0.0873	0.0709
	0.8125	3.0	0.775	0.1096	0.0891
	0.8125	3.2	0.875	0.1088	0.0884
	0.8125	3.0	0.750	0.1061	0.0862
Dogwood (lg)	3.9583	1.7	2.550	0.2306	0.9126
	3.9583	3.0	3.400	0.0987	0.3907
	3.9583	3.5	5.800	0.1237	0.4897
	3.9583	2.5	2.300	0.0962	0.3806
	3.9583	3.5	6.150	0.1312	0.5193
	3.9583	4.0	8.300	0.1355	0.5365
	3.9583	4.5	7.100	0.0916	0.3626
	3.9583	3.0	3.180	0.0923	0.3655
	3.9583	3.4	8.600	0.1944	0.7695
Elderberry	1.9444	1.2	0.450	0.1662	0.3232
	1.9444	2.7	0.550	0.0401	0.0780
	1.9444	3.0	0.650	0.0384	0.0747
	1.9444	3.6	1.200	0.0493	0.0958
	1.9444	3.9	0.895	0.0313	0.0609
Eunoymus	0.5556	1.2	0.050	0.0646	0.0359
	0.5556	1.2	0.060	0.0776	0.0431
	0.5556	2.1	0.120	0.0507	0.0281
	0.5556	2.7	0.150	0.0383	0.0213
	0.5556	2.4	0.160	0.0517	0.0287
	0.5556	3.6	0.250	0.0359	0.0200
	0.5556	2.8	0.250	0.0594	0.0330
	0.5556	1.8	0.090	0.0517	0.0287
	0.5556	3.0	0.150	0.0310	0.0172
	0.5556	4.0	0.150	0.0175	0.0097
Service Berry	0.9722	1.5	0.500	0.2364	0.2298
	0.9722	1.3	1.110	0.6988	0.6793
	0.9722	2.0	0.710	0.1888	0.1836
	0.9722	2.8	1.220	0.1656	0.1609
	0.9722	1.0	1.320	1.4043	1.3653
	0.9722	3.4	2.040	0.1877	0.1825
Mule Fat	0.4170	1.4	0.500	0.6327	0.2639
	0.4170	2.3	0.200	0.0938	0.0391

Table 3. Mean Drag Values Computed from Small Flume Data (after Rahmeyer et al. (1995))

	With Leaves			***Without Leaves***		
Vegetation Type	C_{dd}	C_{df}	C_{dw}	C_{dd}	C_{df}	C_{dw}
Staghorn Sumac	0.0740	0.0550	0.0350	0.0011	0.0008	0.0005
Arctic Blue Willow	0.1178	0.0716	0.0679	0.0011	0.0007	0.0006
Norway Maple	0.6810	0.0342	0.0901	0.0067	0.0003	0.0009
Western Sand Cherry	0.0132	0.0381	0.0199	0.0002	0.0006	0.0003
Common Privet	0.2031	0.0658	0.0875	0.0033	0.0011	0.0014
Blue Elderberry	0.3285	0.1037	0.0730	0.0031	0.0010	0.0007
French Pink Pussywillow	0.3904	0.1904	0.1165	0.0085	0.0041	0.0025
Sycamore	0.0190	0.0454	0.0137	0.0002	0.0005	0.0002
Dogwood 1-1	0.0522	0.0455	0.0561	0.0017	0.0015	0.0018
Dogwood 2-1	0.0527	0.0789	0.0783	0.0011	0.0017	0.0016
Euonymus	0.0111	0.0823	0.0233	0.0004	0.0026	0.0007
Dogwood 3-1	0.0322	0.0597	0.0261	0.0005	0.0010	0.0004

MEASURING VEGETATION DENSITY

The Point Frame Method. The point frame method is derived from the point quadrat concept, which is a well-documented and extensively used technique for measuring percentage *cover,* the proportion of the ground occupied by a perpendicular projection of the plant parts onto the ground. Research has shown the point frame method to be accurate, efficient, and reliable (Dudley 1997). The method consists of pushing pins (*points*) through vegetation and recording whether the pin contacts vegetation (a *hit*) or bare ground. The philosophy behind the technique is that if an infinite number of points are placed in a two-dimensional area, exact cover of a plant can be determined by counting the number of points that contact a plant. To measure percentage cover, pins are lowered through the vegetation until the point *first* contacts either vegetation or bare ground. The point frame method uses a frame, mounted on legs, to guide a row of pins vertically through the vegetation. The percentage cover is determined by:

$$\%\,\text{Cover} = \frac{\text{Number of First Hits}}{\text{Number of Points}}(100) \qquad (3)$$

The point method is based on the mathematical concept of homogeneity of a unit area, or quadrat. A *quadrat* is the term used for a comparatively small sample of any larger area. The limiting value of an area or quadrat, as it becomes progressively smaller, is a *point*. Hence, points are often referenced as point quadrats. Because the true area of a point is nil, only contacts with the pin-*point* are recorded.

Another parameter that is measured by the point frame and closely related to cover is LAI. The LAI is the sum of the *total leaf* area per unit area of ground. LAI is used for evaluating the relationship between leaf area and evapotranspiration, and sunlight radiation and rainfall interception by leaves. Imagine all the leaves lying on the ground of a deciduous forest in the autumn. If there are, on average, three layers of leaves on the ground in a 1-km^2 area, then the LAI would be 3 km^2 of leaf area per 1 km^2. If a pin were inserted through the leaves at any random location, then an average of three leaves would be pierced. LAI is measured using the point frame method by recording *all* contacts (rather than only first hits) with leaves made by the pins as they are lowered through the entire depth of the stand. LAI is then estimated by:

$$\text{LAI} = \frac{\text{Number of Hits with Leaves}}{\text{Number of Points}} \qquad (4)$$

The use of the vertical point frame for measuring LAI has been criticized because it does not measure the *total* leaf area but the area projected onto a horizontal plane, such as the ground. For vertical points, a proportion of the actual leaf area between 100 percent for horizontally oriented leaves and 0 percent for vertically oriented leaves (assuming the leaves have zero thickness) is actually being measured.

Wilson (1960) introduced the term *apparent foliage denseness*, defined generally as the total area of the projections of all the *foliage* in a unit volume of space on to a plane perpendicular to a direction making an angle with the horizontal. Note that the terms "vegetation" and "foliage" are used interchangeably in the current text with reference to all plant parts, rather than just leaves. The angle varies from 90 deg for vertical pins to 0 deg for pins inserted horizontally. Vegetation density Veg_d is the apparent foliage denseness measured at an angle equal to 0 deg. If the pin's area advanced in a horizontal direction through the vegetation (*i.e.*, parallel to the main direction of flow), the projected area of foliage on to a plane perpendicular to the flow is determined by Equation 5:

$$\text{Veg}_\text{d} = \frac{\text{Number of Hits with Vegetation}}{\text{Number of Points}}\left(\frac{1}{\text{D}}\right) \qquad (5)$$

where D is the distance the point is advanced through the vegetation or the length of the pin.

Appendix B presents additional details on the point frame method.

The Board Method. A number of "density board" techniques have been proposed as a means for describing vegetation structure as it relates to wildlife habitat. The current discussion is limited to the method presented by MacArthur and MacArthur (1961) (henceforth referred to as the *board method*) since it is the only board technique that was developed specifically for measuring Veg_d. Measurements taken using the board method are used by biologists to prepare a *foliage height profile*, a plot of the Veg_d versus height. MacArthur and MacArthur first proposed using foliage height profiles as an indicator of bird species diversity, a concept that is now well-recognized among the biological sciences community. Although a considerable amount of research has been conducted that has made use of the board method, little attention has been given to the accuracy of the procedure or repeatability of the results.

MacArthur and MacArthur (1961) proposed that a foliage height profile can be constructed from horizontal observation using a white board, marked by a grid, held at a known height above the ground. The board is moved horizontally away from the observer at that height until 50 percent of the board is obscured by foliage from the viewpoint of the observer. The distance between the board and observer is then measured. Assuming that the vegetation is randomly distributed across the board, the Veg_d at the known height of the board is calculated from the Poisson distribution.

The theory behind the board method can be explained using an analogy with the point method. A person looking horizontally through vegetation will observe a fraction X of the board not obscured by foliage. If a long, stiff wire could be pushed at a random location through the vegetation between the eyes of the observer and board, the number of m contacts made by the wire with vegetation and the fraction X of the board that is visible are related by the formula:

$$e^{-m} = X \qquad (6)$$

which is the first term of the Poisson distribution. For example, a board that is 90-percent obscured by foliage (or 10-percent unobscured) is equivalent to an average of 2.3 hits by a wire that is advanced horizontally through the vegetation from the point in which the observation is made (because $e^{-2.3} = 0.10$).

MacArthur and MacArthur recommended that the board be moved away from the observer until the fraction *X* of the board obscured by vegetation is 50 percent. Therefore, the average number of hits m made by the imaginary wire is constant, ($m = 0.69$ because $e^{-0.69} = 0.50$). The distance D (length of the imaginary wire) between the observer and board and the number of hits m are related to Veg_d by:

$$\mathrm{Veg}_d = \frac{m}{D} \qquad (7)$$

where *m* is the theoretical average number of hits per point. Note that the size of the board is unimportant except that a larger board would provide an average over more vegetation. The dimensions of the board used by MacArthur and MacArthur (1961) were 25.4 cm x 45.7 cm (10 in. x 18 in.).

The Camera Method. In 1969, MacArthur and Horn proposed a technique that utilizes a camera for estimating foliage height profiles in forests. The technique requires a camera with an interchangeable focusing screen feature. The factory-installed focusing screen is replaced by a focusing screen with a grid superimposed. (Installed focusing screens typically show a circle with a line through the center that is used to judge whether or not an object in the viewing screen is in focus.) The camera with a grid in the viewing screen is used to sight through the vegetation (Figure 1). The camera method was originally intended to sight vertically upward through low-canopy forests; however, it is easily adapted for use in the horizontal direction.

To employ the camera method, the observer first views through the camera with the focus set at the minimum distance such that objects close to the observer are clearly in focus. The focusing ring is then rotated, bringing more distant vegetal elements into focus. As the focus ring is rotated, an imaginary line (or point) is erected through the vegetation by each intersection in the grid. When a vegetal element, such as a leaf, comes into focus (a hit) over a grid intersection, the distance to the vegetal element is recorded by reading the distance indicated on the focusing scale on the camera lens. Only *first* hits are recorded. The maximum distance over which measurements are made depends on the density of the vegetation. The maximum distance should be established such that not all of the grid intersections contact vegetation over that distance.

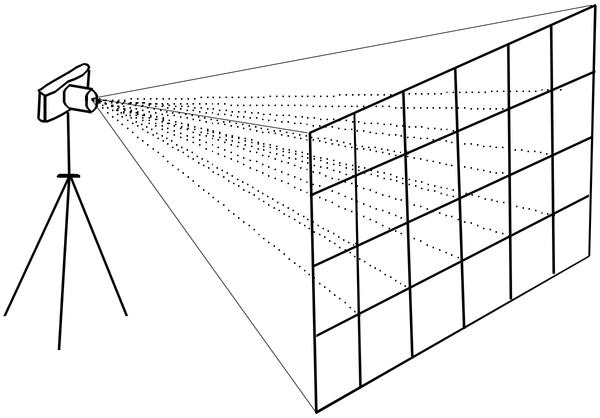

Figure 1. Schematic illustration of concept behind camera method using a grid with 15 intersections. Imaginary points, depicted by dotted lines, are projected through vegetation

The camera method is based on the principle that the Veg_d (D) as a function of the distance between the camera and some plant part viewed through the camera D can be estimated from the distribution of first leaf distance as follows. Let $\varphi(D)$ be the probability of no foliage over the first D (at least) meters. To have no foliage in

D+dD ft, there must be no foliage in both the D and the additional dD. Because the probability of there being no foliage in the additional dD is 1-Veg_d(D)(dD) (one minus the probability of foliage occurring in dD), then

$$j\,(\mathrm{D+dD}) = j\,(\mathrm{D})\,[1 - \mathrm{Vegd(D)(dD)}] \qquad (8)$$

Solving for Veg_d(D) and substituting:

$$\mathrm{Veg}_d\,(\mathrm{D}) = \frac{-1}{j\,(\mathrm{D})}\,\frac{\mathrm{d}\,j\,(\mathrm{D})}{\mathrm{dD}} = \frac{-\,\mathrm{d}\,[\ln j\,(\mathrm{D})]}{\mathrm{dD}} \qquad (9)$$

The total number of plant parts in a line of site is the integrated value of Veg_d (D) between two distances, D_1 and D_2:

$$\int_{\mathrm{D}_1}^{\mathrm{D}_2} \mathrm{Veg}_d\,(\mathrm{D})\,\mathrm{d(D)} = \ln\left[\frac{j\,(\mathrm{D}_1)}{j\,(\mathrm{D}_2)}\right] \qquad (10)$$

The probability of no vegetation being encountered over the distances D_1 and D_2, is estimated from the proportion of the distance measurements that *exceed* D_1 and D_2, respectively. For example, using a grid with 16 intersections, the following measurements to first foliage are recorded in meters (ranked from smallest to largest) over a total distance of 5 m: 0.6, 1, 1.3, 1.6, 1.6, 2, 2, 2, 2.5, 2.5, 3, 3, 3.3, 3.6, 5, 5; where 5 indicates that no foliage was encountered for that grid intersection over a total distance D of 5 m. If $D_1 = 1$ m, the probability of encountering no leaves over that distance, Δ (D_1), is 14/16 (i.e., 14 of the 16 measurements exceed 1 m). Similarly, if $D_2 = 3.3$ m, Δ (D_2) is 3/16. Theoretically, from the equation, the number of hits per intersection between 1 m and 3.3 m is ln[Δ(1)/Δ(3.3)] = ln [(14/16)/(3/16)] = ln 4.67 = 1.54.

APPLICABILITY AND LIMITATIONS

Techniques described in this technical note are generally new in practice to stream restoration, but have undergone peer review in several journal articles. As their use matures, more accurate estimates of vegetation density and drag coefficients are anticipated, and some revision of the methods may be necessary. Previous applications of this technique have been limited to relatively uniform stands of vegetation and an integral form of each equation is required to assess non-uniform vegetation distribution. Existing practice generally requires that the C_{dd} and Veg_d be combined as a lumped parameter and determined empirically. Procedures outlined in this technical note provide insight into the variability and component contributions to this lumped parameter.

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APPENDIX
DRAG COEFFICIENTS AND VEGETATION DENSITIES

Few data are available from which drag coefficients can be computed for vegetation immersed in flowing water. Rahmeyer et al. (1995) present a data set developed under contract to the USAE Waterways Experiment Station. These investigators devised a technique for measuring drag on live vegetation in laboratory flumes using a load cell and strain gage. Various combinations, sizes, and densities of 20 species of vegetation were evaluated for several flow conditions. Table 1 summarizes the drag data. Though extensive measurements of the vegetation were recorded, a density measure such as Veg_d or LAI was not recorded. The C_{dd} values reported herein were estimated from plant morphology data.

Additional data are available for drag coefficients and areas of vegetation subject to wind flow. The drag coefficients derived from wind tunnel or field data for air are equivalent to drag coefficients for water, provided the Reynolds numbers are equal and the vegetation is geometrically similar. Unfortunately, Reynolds numbers and reference areas are seldom recorded with published data; therefore the utility of drag coefficients presented in the literature is limited.

For deciduous vegetation, it is necessary to recognize that both the area and the drag coefficient will vary depending on the condition of the vegetation (leaf on vs. leaf off). Tables 2 and 3 present examples of how these values vary for willows and dogwoods. Drag coefficients and vegetation density values for the data presented in Arcement and Schneider (1989) are given in Table 4. Table 5 presents drag coefficients from other sources.

Table 1 Mean Drag Values Computed from Small Flume Data (after Rahmeyer et. al (1995))

	With Leaves			Without Leaves		
Vegetation Type	C_{dd}	C_{df}	C_{dw}	C_{dd}	C_{df}	C_{dw}
Staghorn Sumac	0.0740	0.0550	0.0350	0.0011	0.0008	0.0005
Arctic Blue Willow	0.1178	0.0716	0.0679	0.0011	0.0007	0.0006
Norway Maple	0.6810	0.0342	0.0901	0.0067	0.0003	0.0009
Western Sand Cherry	0.0132	0.0381	0.0199	0.0002	0.0006	0.0003
Common Privet	0.2031	0.0658	0.0875	0.0033	0.0011	0.0014
Blue Elderberry	0.3285	0.1037	0.0730	0.0031	0.0010	0.0007
French Pink Pussywillow	0.3904	0.1904	0.1165	0.0085	0.0041	0.0025
Sycamore	0.0190	0.0454	0.0137	0.0002	0.0005	0.0002
Dogwood 1-1	0.0522	0.0455	0.0561	0.0017	0.0015	0.0018
Dogwood 2-1	0.0527	0.0789	0.0783	0.0011	0.0017	0.0016
Euonymus	0.0111	0.0823	0.0233	0.0004	0.0026	0.0007
Dogwood 3-1	0.0322	0.0597	0.0261	0.0005	0.0010	0.0004

Table 2 Parametric Data for Dogwood (Fischenich 1995)

Plant Type	**Dogwood 1-1**
Height (in)	17
Stem to First Branch (in)	
Stem Diameter (in)	0.375
No. Stems	1
No. Branches	11
No. Leaves	50
Leaf Thickness (in)	
Leaf Width (in)	0.5
Leaf Length (in)	3
Ave. Branch Diameter (in)	
Height Leaf Area (in)	13
Width Leaf Area (in)	9

Drag and Velocity Data

	With Leaves					**Without Leaves**				
Run #	**Vel. (ft/sec)**	**Drag (lbs)**	**Cd_d**	**Cd_f**	**Cd_w**	**Vel. (ft/sec)**	**Drag (lbs)**	**Cd_d**	**Cd_f**	**Cd_w**
1	1.68	0.108	0.0556	0.0485	0.0598	1.41	0.108	0.00246	0.00214	0.00264
2	2.01	0.162	0.0583	0.0509	0.0626	2.04	0.206	0.00224	0.00195	0.00240
3	2.18	0.201	0.0615	0.0537	0.0661	2.51	0.294	0.00211	0.00184	0.00227
4	2.62	0.245	0.0519	0.0453	0.0558	3.31	0.412	0.00170	0.00148	0.00183
5	3.26	0.392	0.0536	0.0468	0.0576	3.61	0.451	0.00156	0.00137	0.00168
6	3.53	0.480	0.0560	0.0489	0.0602	3.92	0.451	0.00133	0.00116	0.00143
7	4.22	0.593	0.0484	0.0422	0.0520	4.44	0.623	0.00143	0.00125	0.00154
8	4.44	0.618	0.0456	0.0398	0.0490	4.50	0.627	0.00140	0.00122	0.00150
9	4.55	0.647	0.0454	0.0396	0.0488	4.55	0.657	0.00143	0.00125	0.00154
10	4.53	0.642	0.0455	0.0397	0.0489	4.75	0.588	0.00118	0.00103	0.00127

Computed A_d (ft^{-1})	0.7091503
Computed A_f (ft^{2})	0.8125
Computed A_w (ft^{2})	0.6598438

Table 3 Parametric Data for Willow (Fischenich 1995)

Plant Type	**Arctic Blue Willow (Salix purpurea nana)**
Height (in)	22
Stem to First Branch (in)	2
Stem Diameter (in)	0.509
No. Stems	1
No. Branches	50
No. Leaves	700
Leaf Thickness (in)	0.014
Leaf Width (in)	0.125
Leaf Length (in)	1
Ave. Branch Diameter (in)	0.114
Height Leaf Area (in)	20
Width Leaf Area (in)	10

Drag and Velocity Data

	With Leaves					**Without Leaves**				
Run #	**Vel. (ft/sec)**	**Drag (lbs)**	**Cd$_d$**	**Cd$_f$**	**Cd$_w$**	**Vel. (ft/sec)**	**Drag (lbs)**	**Cd$_d$**	**Cd$_f$**	**Cd$_w$**
1	1.02	0.207	0.2415	0.1469	0.1392	1.43	0.129	0.00238	0.00145	0.00137
2	1.32	0.289	0.2013	0.1225	0.1160	1.82	0.155	0.00177	0.00107	0.00102
3	1.79	0.366	0.1386	0.0843	0.0799	2.46	0.207	0.00129	0.00079	0.00074
4	2.15	0.431	0.1132	0.0688	0.0652	2.95	0.224	0.00097	0.00059	0.00056
5	2.34	0.483	0.1071	0.0651	0.0617	3.50	0.272	0.00084	0.00051	0.00048
6	2.73	0.526	0.0857	0.0521	0.0494	4.25	0.345	0.00072	0.00044	0.00042
7	2.92	0.560	0.0797	0.0485	0.0460	4.66	0.397	0.00069	0.00042	0.00040
8	2.98	0.578	0.0790	0.0481	0.0455	4.77	0.440	0.00073	0.00044	0.00042
9	3.48	0.733	0.0735	0.0447	0.0423	4.94	0.466	0.00072	0.00044	0.00042
10	4.39	0.922	0.0581	0.0353	0.0335	5.19	0.517	0.00072	0.00044	0.00042

Computed A_d (ft^{-1})	0.8492618
Computed A_f (ft^{2})	1.3959583
Computed A_w (ft^{2})	1.4732758

Table 4 Veg_d and hydraulic parameters for stream data presented in Arcement and Schneider (1989).

								$C_d = 2.1(VR)^{-1.1}$		$C_d = 0.28(VR)^{-1.1}$	
	Section	Veg_d (1/m)	Q (m^3/s)	V (m/s)	R (m)	VR (m^2/s)	Measured n	Debris C_d	Predicted n	No Debris C_d	Predicted n
Pea Creek	5	0.028	50.4	0.182	0.897	0.163	0.14	15.4	0.14	2.1	0.05
Pea Creek	4	0.033	50.4	0.239	0.683	0.163	0.14	15.4	0.13	2.1	0.05
Coldwater River	2	0.025	125	0.180	0.696	0.125	0.11	20.6	0.13	2.7	0.05
Coldwater River	2	0.030	125	0.180	0.696	0.125	0.11	20.6	0.14	2.7	0.05
Thompson Creek	9	0.038	108	0.117	0.695	0.081	0.20	33.2	0.20	4.4	0.07
Yockanookany River	5	0.027	289	0.265	0.961	0.254	0.12	9.5	0.11	1.3	0.04

Table 5 Example Drag Coefficient Values

Source	*Object*	*Re*	Cd_d	Cd_f	Cd_w
Thom (1968)	**Model Leaf (90^{o} orientation)**			**0.49**	
				0.48	
	Model Leaf (23^{o} orientation)			**0.17**	
				0.15	
	Model Leaf (0^{o} orientation)			**0.05**	
				0.03	
Fraser (1962)	**Spruce (Picea abies)**			**0.57**	
	W. Hemlock (Tsuga heterophylla)			**0.25**	
Uchijima (1976)	**Rice**	**Low**	**0.1**		
		High	**0.01**		
Rauner (1976)	**Birch Forest**	**500000**			**0.023**
		1000000			**0.019**
		1500000			**0.016**
		2000000			**0.016**
	Aspen Forest	**500000**			**0.015**
		1000000			**0.018**
		1500000			**0.02**
	Pine Forest	**500000**			**0.038**
		1500000			**0.046**
		2000000			**0.051**
		2500000			**0.057**