Resistance Due to Vegetation

by Dr. Craig Fischenich[1]

May 2000

Complexity

Low — Moderate — High

Value as a Design Tool

Low — Moderate — High

Cost

Low — Moderate — High

OVERVIEW

Drag is generated when a fluid moves through vegetation. The drag creates velocity gradients and eddies that cause momentum losses. These losses are significant for a wide range of flow conditions, and existing techniques for the prediction of resistance do not take these into account, leading to underpredictions of resistance.

Concepts of drag were employed to formulate two new resistance relations for cases when dense vegetation is present in the floodway:

$$n = K_n R^{2/3} \left[\frac{C_d A_d}{2g} \right]^{1/2}$$

for unsubmerged vegetation, and:

$$n = \frac{K_n R^{1/6}}{(RHS \quad Eqn 17)\sqrt{g}}$$

for fully submerged vegetation. Values for CdAd as a function of vegetation type and flow condition are presented in an accompanying technical note.

PHYSICAL PROCESSES

The primary resistance to the flow of water in unrestricted open channel flows can be attributed to the effect of viscous shear at the boundaries of the channel. This realization led Prandtl (1904) to formulate a logarithmic velocity relation for open channel flows. His proposed logarithmic distribution has been shown to be a good representation of the actual velocity distribution in channels and canals that do not have obstructions in the water column (Chow 1959).

The assumptions Prandtl used to derive the logarithmic velocity distribution are not valid for vegetated floodways. In addition to the viscous shear at the boundaries of the channel, the vegetative elements generate form drag losses. The drag induced by the vegetative elements impedes the flow and causes a deficit in the local velocity.

Fischenich (1996) found that the net effect of this drag on the velocity profile was consistent for all of the data present in the literature, regardless of the vegetation type or flow medium. Figure 1 presents velocity distributions for three flow conditions: unobstructed, submerged vegetation, and unsubmerged vegetation. The deviation from the logarithmic profile for the two cases with vegetation impeding the flow is clear.

Figure 2 shows velocity plots for several vegetation types and flow conditions. The heights and velocities are normalized for comparative purposes. The profiles display similar characteristics; retarded velocities and a near-zero velocity gradient within the lower

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portion of the vegetation canopy, a zone near the top of the vegetation with a very high velocity gradient, and an approximately logarithmic distribution above the vegetation.

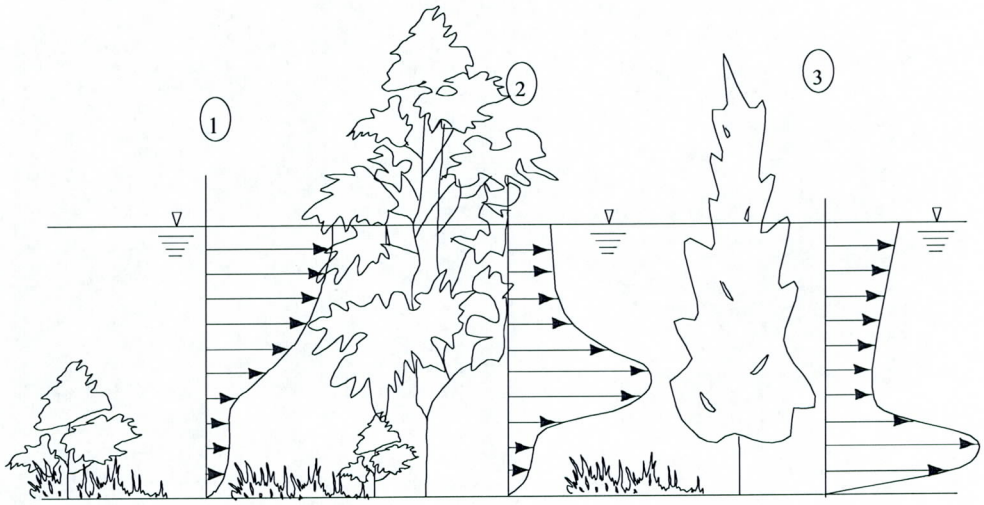

Figure 1. Velocity distribution for submerged and unsubmerged vegetation. Velocity distribution represents vegetation condition to the left

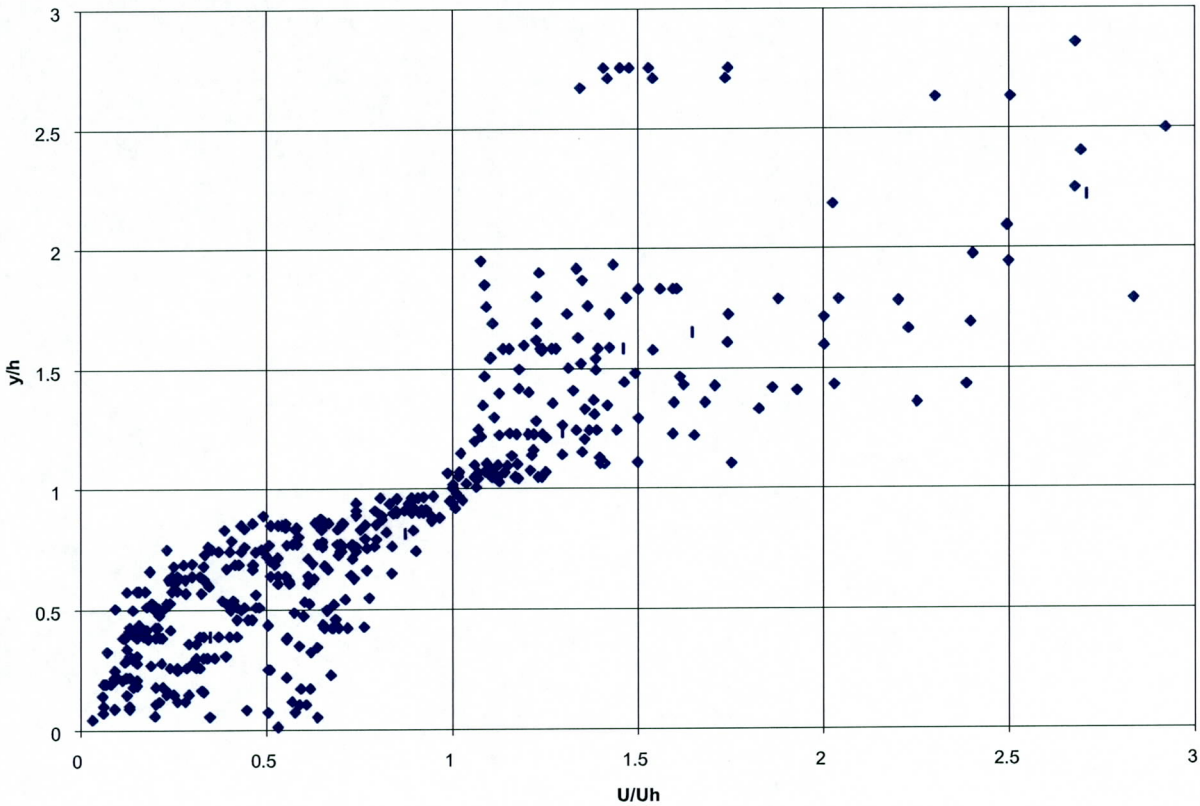

Figure 2. Normalized velocity distributions for various types of vegetation and flow conditions. The combined data represent 27 analyses of grasses, 23 analyses of shrubs, and 16 analyses of trees

Because vegetative drag can have a profound effect on the velocity and, thus, the water surface elevation, any expression of the flow conditions in a vegetated channel must include drag. The general relation for drag is:

$$F_d = \frac{\rho}{2} C_d A V^2 \qquad (1)$$

where

F_d=drag force (ML/T^2)
ρ=fluid density (M/L^3)
C_d=an empirical, dimensionless drag coefficient
A=area of the obstruction normal to the flow (L^2)
V =approach velocity of the fluid (L/T)

Fenzl and Davis (1964) found that the relative influence of the vegetation drag and the soil shear for unsubmerged vegetation is a function of the height above the bed z relative to the height of the vegetation h and two heights z_1 and z_2 between z = 0 and h that are a function of the sediment gradation and the vegetation properties (Figure 3). They determined that:

1) For a range of small depths of flow ($z < z_1 < h$), soil roughness is the predominant source of hydraulic resistance. Under these conditions, resistance decreases with increasing depth of flow.
2) At some greater flow depth ($z_2 < z < h$), resistance becomes essentially independent of small changes in soil roughness and increases with increasing depth of flow.
3) For intermediate depths ($z_1 < z < z_2$), resistance is influenced by both soil and vegetative roughness.

Fenzl and Davis found that the ratio of resistance due to soil roughness to total resistance decreased from a value of 0.5 at a depth of flow of 0.1 ft, to 0.07 at a depth of 0.2 ft. Thus, the significance of the soil properties within the vegetated portion of the floodway is significant only for very shallow flows, and vegetative drag is the dominant source of momentum loss under most flow conditions.

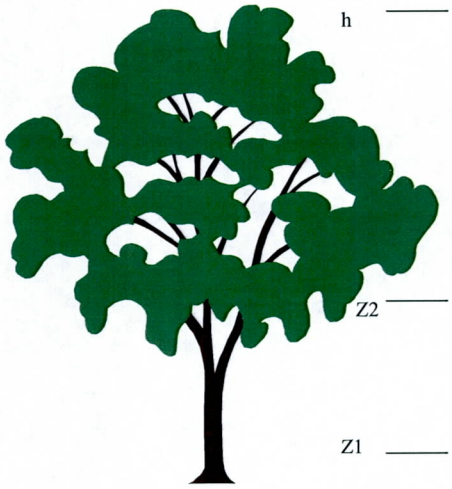

Figure 3. Parametric description for Fenzl and Davis (1964) relations.

RESISTANCE FOR UNSUBMERGED VEGETATION

A relation for unsubmerged vegetation can be formulated from the principle of conservation of linear momentum. Following a derivation similar to that for the de Saint Venant Equation, the sum of the external forces in a control volume (CV) is equated to the rate of change of linear momentum:

$$\Sigma F = ma = m\left(\frac{dV}{dt}\right) \qquad (2)$$

Considering only the x-component of the linear momentum, the right side of Equation 2 can be expanded to form Equation 3 as follows:

$$\frac{dM}{dt} = \frac{\partial}{\partial t}\left[(\rho VA)\Delta x + \left(\frac{\partial \rho V^2 A}{\partial x}\right)\Delta x - (\rho q_s U_s)\Delta x\right]$$

The external forces include gravity (F_g), pressure (F_p), drag (F_d), and friction (F_f), for which the x-component which can be described as:

$$F_g = \rho g A \Delta x S_o \qquad (4)$$

$$F_p = -\rho g\left(\frac{dy}{dx}\right)A\Delta x \qquad (5)$$

$$F_d = -\frac{\rho}{2}C_d A_d V^2 A\Delta x \qquad (6)$$

$$F_f = -\rho g A\Delta x S_f \qquad (7)$$

where
Fg = external gravity force on the CV
So = bed slope
Fp = external pressure force on the CV
F_d = external drag force exerted by the vegetation on the CV
$A_d = \sum A_i / A\sum x$ = vegetation density per unit channel length L^{-1}
F_f = external friction force due to shear on the boundary
S_f = friction slope (i.e. the slope of the momentum grade line)

Collecting these terms and rearranging, the left-hand side of Equation 2 gives:

$$\Sigma F = A\rho g\Delta x\left[S_o - S_f - \frac{C_d A_d V^2}{2g} - \frac{dy}{dx}\right] \qquad (8)$$

Using Equations 3 and 8, assuming the seepage inflow and the boundary shear are negligible, and rearranging yields Equation 9:

$$\frac{A_d C_d}{2g} = \frac{S_o}{V^2} - \frac{1}{gV^2}\frac{dV}{dt} - \frac{1}{gV}\frac{dV}{dx} - \frac{1}{V^2}\frac{dy}{dx}$$

which is the unsteady, gradually varied version of the de Saint Venant Equation for linear momentum replacing the boundary shear term with a drag term. The corresponding steady, gradually varied equation is:

$$\frac{A_d C_d}{2g} = \frac{S_o}{V^2} - \frac{1}{gV}\frac{dV}{dx} - \frac{1}{V^2}\frac{dy}{dx} \qquad (10)$$

and the steady, uniform equation is:

$$\frac{V^2 A_d C_d}{2g} = S_o \qquad (11)$$

Equating the slope term in Equation 11 to the slope term in Manning's Equation, a relation for Manning's n is established as:

$$n = K_n R^{2/3}\left[\frac{C_d A_d}{2g}\right]^{1/2} \qquad (12)$$

Alternative derivations of Equation 12 from energy or shear considerations are possible. The form varies depending on the assumptions made. Equation 12 requires an estimate of the drag coefficient C_d and the corresponding vegetation area. These are discussed in further detail later in this chapter. This equation is applicable only when the vegetation is unsubmerged because it does not account for the momentum flux downward into the canopy that occurs with overtopping flows (Figure 4). The following section addresses submerged vegetation cases.

Figure 4. Example of flow through unsubmerged vegetation

RESISTANCE FOR SUBMERGED VEGETATION

Equation 12 does not work well when the vegetation is fully submerged because it does not take into account complex flow conditions above the flow canopy that can increase or decrease overall resistance depending on the depth of flow and the Reynolds number. However, normalized velocity profiles for this case are definitive, and present an alternative approach to the derivation of a resistance relation.

Meteorologists and fluid mechanicists involved with wind power generation, soil erosion control, crop management, and other related activities have studied the behavior of winds inside and directly above forest canopies and crops. A modified logarithmic law describing turbulent velocity profiles has been proposed by most investigators for situations when stratification has only a minor influence, and can be summarized by Equation 13, below:

$$\frac{u}{U_*} = \frac{1}{k}\ln\left[\frac{(z-d)}{z_o}\right] \qquad \text{For } (z-d)/z_0 \geq 1 \quad (13)$$

where

u = local velocity

$U_* = (\tau/\rho)^{1/2}$ is the friction velocity

d = zero-plane displacement

k = von Karman's dimensionless shear layer constant

z = height above the ground

z_o = surface roughness

Figure 5 graphically presents the parameters in Equation 13. The z_o term is generally taken to represent a mean value across an uneven surface and is often eliminated from the numerator. The displacement thickness d is important for tall roughness elements such as long grasses, agricultural crops, forests, and thick riparian vegetation. In the absence of roughness elements or when they are sufficiently short, the displacement height is zero. The parameters z_o and d are usually determined from measured wind profiles.

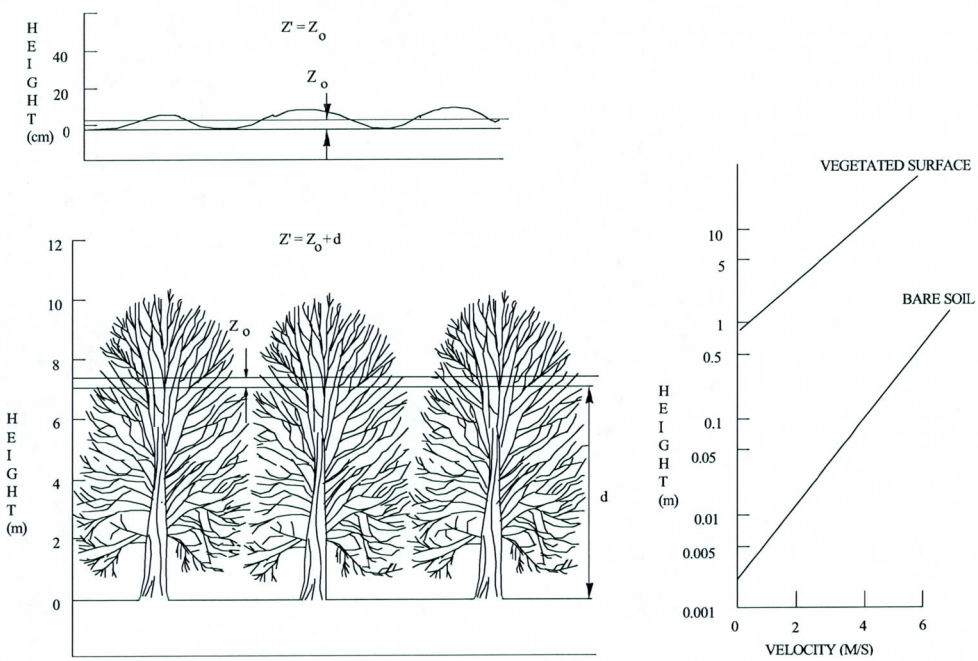

Figure 5. Velocity displacement method

It is customary to assume the von Kármán constant k = 0.4, to specify displacement height as a function of the vegetation characteristics and to solve for friction velocity and surface roughness height by fitting Equation 13 to measured data. Surface roughness estimates have been estimated for flow data obtained over different agricultural crops and forests. A variance in the results approaching an order of magnitude is common, even for flow over the same surface. Experimentalists frequently fail to obtain data above the wake region of individual roughness elements (z > l.5h); sometimes the data are taken during non-neutral conditions; and often upwind nonhomogeneities distort the measured profiles. Table 1 summarizes various investigators' estimates of z_o and d. In Table 1, s is the plant spacing, S is silhouette area (the total area of the plant projected normal to the flow), C_f is the shear stand drag coefficient, and other terms are as previously defined.

Equation 13 has been found to be a good expression of the fluid velocity profile for that portion of the profile above about 2/3 h. However, it does not accurately represent the profile within the lower portions of the vegetation canopy. For flow within the vegetation canopy, different profiles have been proposed by meteorologists using first- order closure models that specify an eddy diffusivity K and a drag coefficient C_d for constant foliage distribution. However, none of these expressions are consistent with the observed zero velocity gradient within the lower half of the vegetation canopy. Fischenich (1996) determined that the velocity profile within the canopy could better be approximated by:

$$\frac{u}{u_h} = \left(\frac{\cosh(\beta\xi)}{\cosh(\beta)} \right)^{0.5} \qquad (14)$$

Table 1. Formulae for Roughness Length Z_o and Displacement Thickness d

Author	*Z_o =*	*d =*
Lettau (1969)	h(0.5(s/S))	
Massman (1987)	1.07(h-d)e**(-k(Cf/2)**.5)	h*f(C_dLAI)
Meroney (1993)	0.1h < zo < 0.13h	0.67h < d < 0.75h
Otterman (1981)	0.5h(1-e**(-s/S))	
Paeschke (1937)	h/7.35	
Seginer (1974)	(lh/k)exp((-4k**3)/(lhC_da))**.33	h-lh/k
Sellers (1965)	2.5 + ln h (h in cm)	
Standhill (1969)		0.64h

where

$$\beta = \left(\frac{2 C_d A_d h u_h}{K_h} \right) \qquad (15)$$

In Equations 14 and 15,

u = local velocity
u_h = velocity at the top of the undeflected vegetation
h = undeflected vegetation height
z = height above the ground
ξ = z/h
C_d = a stand drag coefficient
A_d = vegetation area based on density
K_h = eddy diffusion coefficient

Fischenich (1996) investigated the relationships between the lumped drag-area term C_dA_d and the z_o and d terms in Equation 15. He found that these parameters could be approximated as functions of C_dA_d and that, by replacing the K_h term in Equation 15, an expression for the mean velocity could be reduced to a function of the vegetation height h the flow depth y and the lumped drag-area term C_dA_d (Equation 16):

$$\frac{V}{U_*} = \frac{2.5}{y} \left[\int_0^h 1.26 h^2 \left(\frac{e^{(11 C_d A_d \frac{z}{h})}}{e^{(11 C_d A_d)}} \right)^{0.5} dz + \int_h^y \ln \left(\frac{\frac{z}{h} - .95}{0.13 e^{-(C_d A_d - 0.4)^2}} \right) dz \right]$$

Fischenich's general equation is rather difficult to work with, but can be reduced to a simpler form with some limiting assumptions. Assuming the C_dA_d value remains below unity and the flow depth is not more than twice the height of the vegetation, estimates of within 5 percent of the actual velocity can be obtained by solving the integrals in Equation 16 to yield:

$$\frac{V}{U_*} = \frac{2.5}{y} \left[\begin{array}{l} \left(\frac{0.23 h^3}{C_d A_d} \right) - (1.2 + 2 C_d A_d)^* \\ \left(y - 1.15 h - 0.05 \ln \left| \frac{y}{h} - 0.95 \right| \right) \end{array} \right] \qquad (17)$$

By noting that Manning's n value can also be expressed in terms of V/U, the right-hand side (RHS) of Equation 17 can be used to obtain a value of Manning's n for a particular flow depth y as follows:

$$n = \frac{K_n R^{1/6}}{(RHS \quad Eqn\, 17)\sqrt{g}} \qquad (18)$$

Equation 18 is applicable only in cases where the depth of the flow exceeds the height of the vegetation. Initial results of studies by Fischenich (1996) suggest that the practical application of Equation 18 is restricted to cases where the depth of flow is at least 1.1y, though additional verification is needed. Because the flow depth must be specified, the equation can be solved by iteration when making normal depth computations or can be used to construct a NV card for HEC-2 analyses. The vegetation height and a value for C_dA_d must be known in addition to the flow depth. Measurements of the vegetation height are relatively straightforward. Specifying appropriate values for Cd and A is the subject of an accompanying technical note.

APPLICABILITY AND LIMITATIONS

Techniques described in this technical note are applicable to stream restoration and assessment projects that include flood conveyance as an objective, and where riparian vegetation is subject to flooding.

The range of applicability for the two resistance equations has not been fully explored. However, the assumptions made in their derivation, early applications to field data, and observations from laboratory studies, suggest some preliminary limitations. Applicability is limited to steady uniform flow for the unsubmerged case (or at least quasi-steady, quasi-uniform flow). Properties that likely define the equation's applicability include:

relative flow depth, Reynolds number, soil particle size, and vegetation density.
Work by Fenzl and Davis (1964) suggests that a minimum flow depth of approximately 0.1 h is needed for the assumption of negligible shear to be accurate. The actual minimum depth should be a function of the soil particle size and vegetation density, but this relation cannot be defined currently. At sufficiently great depths, drag should be only a small component of resistance and flow can be assessed using the relation represented by Equation 12. Again, vegetation density would play a role in defining this depth, but a value of 20 h should be a conservative estimate. Equation 19 is suggested for y>20:

Equation 19 is based upon the relative roughness of sands, gravels, and cobbles. It is

$$n = \frac{k_n y^{1/6}}{\sqrt{g}\, 5.75 \log(\frac{4y}{h})} \qquad (19)$$

not a continuous function with Equation 18, but either should yield reasonable values of resistance for flow depths in the range of 20h.

Vegetation density is a critical determinant in the degree of drag experienced and can help define the applicability of the equations. A closely related issue is the definition of vegetation area for the drag relation. The drag coefficients needed for the application of Equations 12 and 18 also depend upon the definition of vegetation area, as addressed in an accompanying technical note.

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POINT OF CONTACT

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REFERENCES

Chow, V.T. (1959). *Open-channel hydraulics.* McGraw-Hill, New York.

Fenzl, R.N., and Davis, J.R. (1964). "Hydraulic resistance relationships for surface flows in vegetated channels." *Transactions of the American Society of Agricultural Engineers 7*, 46-51, 55.

Fischenich, J.C., (1996). "Velocity and resistance in densely vegetated floodways," Ph.D. diss., Colorado State University, University Press, Fort Collins, CO.

Lettau, H. (1969). "Aerodynamic roughness parameter on the basis of roughness element description," *J. of Applied Meteorology* 8, 828-832.

Massman, W. (1987). "A comparative study of some mathematical models of the mean wind structure and aerodynamic drag of plant canopies," *Boundary-layer meteorology* 40, 179-197.

Meroney, R.N. (1993). "Wind-tunnel modelling of hill and vegetation influence on wind power availability," Literature Review, CSU Report CER92-93-RNM-1, Colorado State University, Fort Collins, CO.

Otterman, J. (1981). "Plane with protrusions as an atmospheric boundary," *J. Geophysics Research*, 86, 6627-6630.

Paeschke, W. (1937). "Experimentelle Untersuchungen z. Ravhikeits und stabilitats problem in der bodennahen Luftschich," *Beitr. Phys. D. fr. Atmos*, 24, 163-189.

Prandtl, L. (1904). "Über Flüssigkeitsbewegung bei sehr kleiner Reibung," *Verhandlung III Internationler Mathematische Kongress, Heidelberg 1904*.

Seginer, I. (1974). "Aerodynamic roughness of vegetated surfaces," *Boundary Layer Meteorology* 5, 383-393.

Sellers, P.J., Mintz, Y., Sud, Y.C., and Dalcher, A. (1986). "A simple biosphere model (SiB) for use within general circulation models," *Journal of Atmospheric Sciences* 43(6), 505-531.

Standhill, G. (1969). "A simple instrument for the field measurement of turbulent diffusion flux," *J. Appl. Meteorology*, 8, 509.