Review on Resistance Force to Open Channel Flow through Emergent Vegetation

Abubaker Ali Alamailes

Misurata University, Civil Engineering Department, Libya

Article information	Abstract
Key words *Open channel flow, vegetation, resistance force, bed shear force* *Received 26 9 2022,* *Accepted 22 10 2022,* *Available online 01 11 2022*	***In this study, the resistance force characteristics formed by emergent vegetation in open channel flow has been reviewed. In vegetated open channels, the total flow resistance is controlled by the combination of drag force caused by vegetation and bed shear force. Different approaches have been used to model the drag force caused by vegetation and roughness of channel bed. Conventional equations such as Manning's equation or Darcy-Weisbach have been used to play an important rule to investigate these phenomena. Recent researches indicated that Manning's equation should not be used when flow is relatively slow and channel depth is not constant. However, recently, new approaches such as Kármán Vortex Street or Large Eddies Simulation (LES) are utilized as flow interpreters through vegetation. Different vegetation arrangements (e.g., lined, staggered, grid, and random) were studied and different results were obtained in estimating the drag force and drag Coefficient (C_d) in the system. In general, Vegetation density and approach velocity are the characteristics that control the drag force amount exerted by vegetation.***

I. INTRODUCTION

Flow resistance in water bodies such as wetlands and open channels was established as early as a century ago. In 1926 the flow characteristics passing through vegetation was studied for the river flooding capacity problem in the U.S. (WU 2008). From the historic perspective, vegetation in open channels has been considered by hydraulic specialists as a source of flow resistance, backwater profiles, fate and transport of sediments ((López, F., & García, M. 1998); (Yen 2002)). Later on, vegetation in aquatic environments have achieved another level where it becomes a part of the technique that is used to stabilize the channel sides, provide food for animal, and add an aesthetic view to the environment (Haslam, S. M., & Wolseley, P. A. 1981). Early studies about resistance flow characteristics had been measured over different vegetation crops such as beans (Thom 1971), Corn (Shaw, R.H., G. den Hartog, K.M. King, and G.W. Thurtell, 1974), over forests (Oliver 1971).

In non-vegetated open channels, the resistance force exerted by the total bed and channel sides shear forces (Powell, D. M. 2014). However, vegetation exerts considerable drag force by diminishing the mean flow through vegetated zone. A number of studies such as those by (Kao 1978), (Klaassen, G., & Van der Zwaard, J. 1974), (Kouwen, N., & Moghadam, F. 1996), (Li, R., & Shen, H. W. 1973), (Nepf, H., & Vivoni, E. 1998), (Nepf 1999), and (Thompson, G. T., & Roberson, J. A. 1976), have been carried out for estimating the flow resistance due to drag of the vegetation stems. In vegetated open channels the total flow resistance is controlled by the combination of drag force caused by vegetation and bed shear force (Kothyari, U. C., Hayashi, K., & Hashimoto, H. 2009). In general, vegetation drag controls the resistance of flow in vegetated channels and bed shear force can be ignored (Fenzl 1962), (Temple, D., Robinson, K. M., Ahring, R. M., & Davis, A. G. 1987), (Stone, B. M., & Shen, H. T. 2002). On the other hand, sediment transport in dense vegetated open channels (Tsujimoto 1992), (Baptist 2005), (Jordanova, A. A., & James, C. 2003) indicates that bed particle resistance in vegetated open channel flows should not be neglected. The drag force exerting by the vegetation is by its stem and leaves.

When a fluid flows through vegetation, the type and the density of vegetation as well as the depth and velocity are the characteristics that mainly control the flow (Fathi-Moghadam, M., & Kouwen, N. 1997). The density of vegetation has taken as the ratio between the occupied area of the vegetation canopy to cross sectional area of the open channel flow (Kadlec 1990) or the number of stems per unit channel bed area (Stone, B. M., & Shen, H. T. 2002). The correlation of the drag force and the vegetation density has been studied with concentrating on the drag force effect on a single stem then generalizing to the whole vegetation canopy (Burke, R. W., & Stolzenbach, K. D. 1983), (Cheng, N., & Nguyen, H. T. 2011). Until now the effect of various kind of arrangements on the flow have been investigated (i.e. staggered arrangement (Ishikawa, Y., Mizuhara, K., & Ashida, S. 2000), (James, C., Birkhead, A., Jordanova, A., & O'sullivan, J. 2004), random arrangement (Tanino, Y., & Nepf, H. M. 2008), linear arrangement (Liu, D., Diplas, P., Fairbanks, J., & Hodges, C. 2008) and grid arrangement (Takemura, T., & Tanaka, N. 2007).

. Furthermore, in some instances the drag force effects on colony type stems arrangement (i.e., grid, staggered) has been investigated (Takemura, T., & Tanaka, N. 2007). In most of the cases vegetation stem considered as rigid element. However, some researchers have taken in consideration the flexibility of vegetation (Fathi-Moghadam, M., & Kouwen, N. 1997), (Nehal, L., & Ming, Y. Z. 2005), (Järvelä 2004).

Studies on vegetation effects on the water flow have been partitioned into investigation on emergent (unsubmerged or non-submerged) vegetation and submerged vegetation. In this review study, the concentration is on the drag force exerted on emergent vegetation in open channels and to follow up with the progress that has been accomplished to estimate the flow resistance parameters.

II. FLOW RESISTANCE

Resistance to flow is associated with boundary turbulence due to surface features, geometrical borders, obstacles and other elements leading to a loss of energy. Consequently, a resistance coefficient represents the dynamic actions in terms of momentum or energy losses. In the open channel, resistance to flow can be described by of four components including: form drag, skin drag, shape drag, and other parameters such as wind and wave resistance and suspended material existed in flow.

Flow resistance is a major control of the hydraulics of open-channel flow. It defines the quantity of flow that can be transferred in a channel under the condition of changeable velocity and flow depth. Flow resistance is a result of viscous and pressure drag over the wetted boundaries. Therefore, a comprehensive understanding of flow resistance is required for simplifying the problematic analysis on flow in open channels (Ferguson 2010).However, the complexity of the flow resistance is increased in the presence of vegetation in the flow path. In the conventional analysis approaches, it was frequently assumed that the vegetation area is adequately large and the flow at the status of steady uniform flow or steadily changing flow. Though, this assumption does not come to an agreement with real circumstances, since the flow depth in vegetation area declines gradually along the channel and the hydraulic gradient is large (WU 2008). In a vegetated open channel, this drag can be theoretically divided into three sources including: the total amount of viscous drag on the bed surface and pressure drags on soil, pressure drag associated with large non-vegetated boundaries, and drag on the vegetated elements. For most vegetated channels, drag on the vegetated elements dominate the flow resistance (Temple, D., Robinson, K. M., Ahring, R. M., & Davis, A. G. 1987)

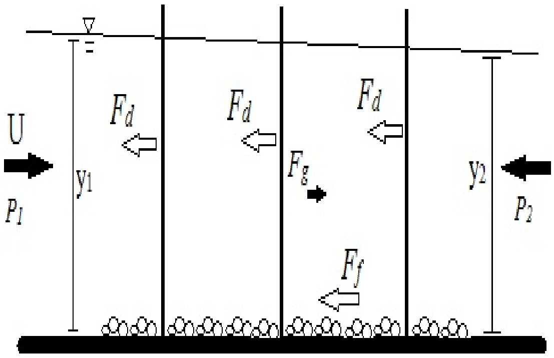


Figure 1. Schematic image of the forces acting on the flowing fluid through emergent vegetation.

Figure 1 depicts the resistance force exerted on the flow is combination of the bank shear force and drag force exerted by obstacles (It is assumed that air friction force on water surface is negligible comparing to other exerted forces).

III. BED FRICTION FORCE

Over the past few centuries, a number of formulas have been established to describe the roughness of channel components. Even though these formulas were firstly used to simulate the flow in pipes, they have been lately used to describe resistance to flow in open channels. Generally, these formulas depend on a constant roughness coefficient to describe the roughness and the resistance of the bed and the sides of a channel. For instance, Chézy (1769) derived the following equation:

$$U = C\sqrt{R.S} \tag{1}$$

Where U is the velocity of the water flow, S is the slope of the channel bed, C is the Chézy coefficient, which represent the roughness of the bed and banks, and R is the hydraulic radius which can be calculated as

$$R = A/P_e \tag{2}$$

Where A is the cross sectional area of the channel and P_e the wetted perimeter.

When Chézy furmula is used, the higher value of the Chézy coefficient represent smoother bed and banks.

Another formula called Darcy-Weisbach was derived after combining tow formulas (Weisbach 1845 and Darcy 1858) and the combination yielded this equation:

$$u = \sqrt{\frac{8g}{f}}\sqrt{RS} \tag{3}$$

Where f is the Darcy-Weisbach roughness coefficient, g is the gravitational acceleration.

Open channel flows are usually described by the Manning's equation which was derived in 1889 for uniform open-channel flow (French 1985)

$$U = \frac{1}{n_m} y^{2/3} S^{1/2} \tag{4}$$

Where n is Manning's roughness coefficient which usually determined by using tables such as in Chow (1953) and y is the flow depth. The presumption is for turbulent flow, which sounds rational for a lot of open channel situations. The total friction force is applied by the bank of the wide-open channel. The more suitable equation for laminar flow is

$$U = \frac{\rho g y^2}{3\mu} S \tag{5}$$

Equations (4) and (5) were combined to arrange a formula to describe the flow for either or the situation of transition (Kadlec 1990):

$$S = \frac{3\mu}{\rho g y^2} U + \frac{n^2}{y^{4/3}} U^2 \tag{6}$$

At situations where the depth Reynolds number $(R_y = y\rho v/\mu)$ is less than 500, the first term controls; at higher velocities second term dominates where the depth Reynolds number is greater than 12500 (see Ergun 1952). Local velocity is depth dependence, because the effects of the bottom drag decreases with moving upward from the channel bottom. General relation between the roughness coefficients can be written as: (Galema 2009)

$$C = \sqrt{\frac{8g}{f}} = \frac{1}{n_m} y^{1/6} = \frac{U}{y\,.\,S} \tag{7}$$

A. Bed Friction in Vegetated Channels

In densely vegetated open channels most of the resistance force is because of the drag force exerted by vegetation foliage and stems.

Kim and Stoesser (2011) claimed that contribution of bed friction depends on vegetation density which is exponentially increases with decreasing the vegetation density, Φ, which is area occupied by vegetation stem per unit length ($\Phi = N\pi d^2/4$) and the assumption of neglecting the bottom friction is invalid for the vegetation density less than 0.016. Where N is the number of the stems per unit area and d is the stem's diameter. In case of the presence of trees, bed friction factor cannot be neglected even in dense arrangement of trees (Ishikawa, Y., Mizuhara, K., & Ashida, S. 2000). So their empirical equations included friction force contribution as well which will be discussed further.

IV. VEGETATION DENSITY

Considering the effect of the fluid viscosity, the friction of the non-vegetated boundaries of the channel, and the gradient of the channel bed, the most important parameter that affects the flow condition in emergent situation is the density of vegetation. In real experiments on vegetation, the density of vegetation can be explained by the (A_m/a) ratio, where A_m, is momentum absorption area (MAA = projection of area of leaves and stems in cross-flow direction of flow) and a, is the horizontal area of vegetation canopy (Fathi, 1997). $(A_m/\forall)h$ also can be defined as vegetation density which is the normalized depth average of the cumulative (A_m/a), where it is calculated based on a linear relationship between the MAA per unit area (A_m/a), and relative depth of submergence (y/h), where h, is the average height of the vegetation in canopy and $\forall$ is the canopy volume (Kowen et al., 2000). In artificial simulated experiments (cylinder arrays), vegetation density considered as area of the bottom occupied by stems (Nepf 1999) or it can be considered as the number of cylinders per unit horizontal area of array including the area occupied by cylinders ($\Phi = N\pi d^2/4$) (Tanino and Nepf, 2008; Kim and Stoesser, 2011). Another definition of vegetation density is the ratio of the area occupied by trees (stems), $\lambda_s = \pi d^2/4L^2$. Ishikawa *et al.* (2000), here, d, is tree diameter, L, is spacing between the trees.

V. DRAG FORCE EXERTED BY EMERGENT VEGETATION IN OPEN CHANNEL FLOW

The mean velocity of flow through emergent vegetation is simpler to calculate than the mean velocity of flow through submerged vegetation, because the velocity is not impacted by a higher velocity above and inside the vegetation.

In 1975, Petryk and Bosmaijan derived an equation by balancing the forces acting on the flow with the drag force. The forces exerting on the flow include: wall roughness, gravity force, forces on the boundary due to shear of water viscosity, and drag forces on the stems. In case of steady uniform flow conditions, the sum of these forces in the flow direction is equal to zero. The bed shear stress was ignored and the following equation was derived:

$$\rho g S - F_d = 0 \tag{8}$$

Where F_d is the drag force, which can be expressed as:

$$F_d = \tfrac{1}{2}\, C_d \,.\, \rho . U^2 . a \tag{9}$$

Where a is the projected area of the vegetation, C_d is the drag force coefficient.

Based on the balance of force, Wu (1999) stated that the following equation can be used to calculate vegetation drag force (F_d) in the direction of the open-channel flow:

$$F_d = C_d\,(\lambda A l)\,\frac{\rho U^2}{2} \tag{10}$$

Where C_d = drag coefficient; λ = vegetal area coefficient representing the area fraction per unit length of channel and the magnitude of is dependent upon the vegetation type, density, and configuration; and Al = total frontal area of vegetation in the channel reach l. The balance between the drag Force and gravitational force $F_G = \rho g(Al)S$ yields:

$$C_d' = \frac{2gS}{U^2} \tag{11}$$

Where $C_d' = \lambda C_d$

Wu derived a formula that expresses the relation between roughness coefficient n_b and C_d' :

$$n_b = \left(\frac{y^{2/3}}{\sqrt{2g}}\right)\sqrt{C_d'} \tag{12}$$

Generally, studies on exerted drag force by emergent vegetation are based on Conventional equations (i.e. Maning's equation and Darcy-Weisbach equation), Petryk and Bosmaijan Drag force equation, numerical modelling and studies based on Von-Karman Vortices Street. The results of the researches based on mentioned approaches will be discussed in coming sections.

A. Drag Force Exerted by an Isolated Single Stem

It is believed that drag force effects due to vegetation are solely and each stem or leaf implies independently of its side ones. The sum of all such drag produces a hydraulic gradient, or friction slope. Thompson and Roberson (1976) presented a summary of calculation resulted from uniformly spaced, vertical, submerged and cylindrical shape objects. The frictional drag on a sole cylinder represented as in Eqn. 9. Drag coefficients which are available in Bennett and Myers (1982) are functions of the stem Reynolds number ($R_d = d\rho v/m$) as depicted in Figure (2).

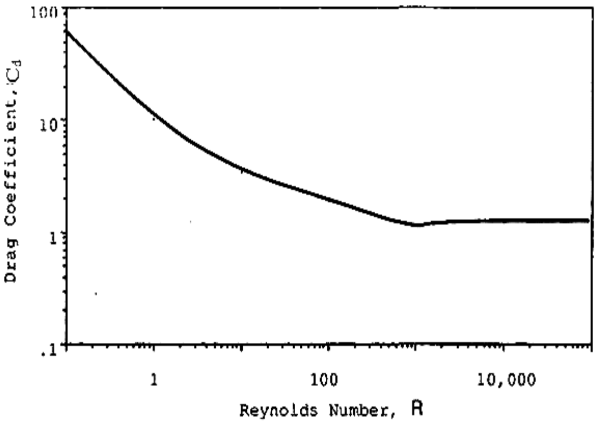


Figure 2. Drag coefficient for infinite single cylinder (Kadlec 1990).

Burke and Stolzenbach (1983) established this correlation's validity for stems of *Spartina* marsh, and they determined that the value of C_d=2.5 worked for their entire velocity range. As it is obvious in Figure 2, this value represents the transition region. The pressure drop (pgS) which is the drag force per unit volume may be calculated as the number of the stems times the stem drag per unit volume:

$$pgS = \frac{m}{h}\,F_d \tag{13}$$

Where m is the stem density (cylinders per unit horizontal area) and h is the height of submerged stem (cylinder).

Kadlec (1990) states that, the drag coefficient is around unity for high flow rates and around $10/R_D$ for low flow rates. In addition, the friction slope obtained as follow:

$$S = \frac{5m\mu}{\rho g}U + \frac{md}{2g}U^2 \tag{14}$$

The first term controls when the stem Reynolds number is less than five; and the second term dominates when the stem Reynolds number is greater than 1,000.

Isolated cylinder subjected to a uniform cross flow may induce a variation of drags, related to its diameter d, the incident flow velocity U, and the kinematic viscosity of fluid v. This variation is associated closely with different flow separation phenomena around the cylinder (Kundu et al. 2004; Niemann and Holscher 1990; Williamson 1996; Zdravkovich 1997).

Kothyari (2009) obtained a good relationship for calculating C_d using the following equation for rigid cylinder in subcritical flow

$$C_d = 1.53[1 + 0.45 \ln(1 + 100\lambda)]R_d^{-3/50} \qquad (15)$$

This equation confirmed for isolated cylinder (λ=0) and the result figured out in the following figure (Fig 3).

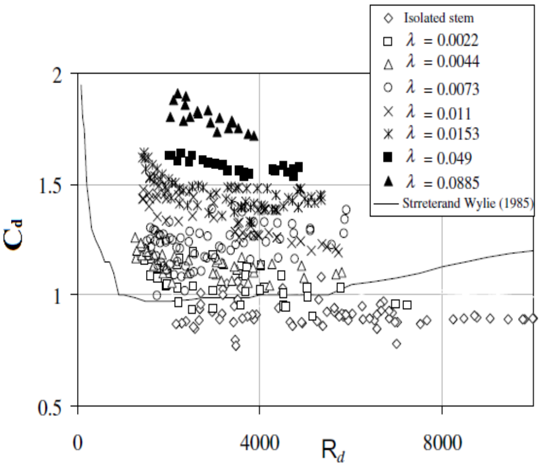


Figure 3. Variation of drag coefficient (C_d) with Reynold's number (R_d) and vegetal area coefficient (λ) (Kothyari (2009).

Cheng (2013) developed an empirical equation for drag coefficient and drag force acting on a single stem utilizing the data set provided by Wieselsberger (1922), Finn (1953), Tritton (1959), and Jayaweera and Mason (1965) (Fig 4). The equation is applicable for the wide range of Reynolds number (i.e. 0.02-200,000).

$$C_d = 11R_d^{-0.75} + 0.9\left[1 - \exp\left(-\frac{1000}{R_d}\right)\right] + 1.2\left[1 - \exp\left(-\left(\frac{R_d}{4500}\right)^{0.7}\right)\right] \qquad (16)$$

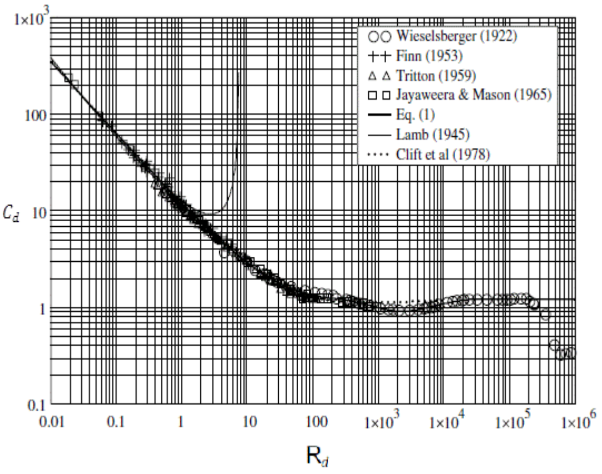


Figure 4. Variation of drag coefficient C_d with Reynolds number (R_d= Ud/ν) for a single isolated cylinder subject to a cross flow (Cheng 2013).

B. Densely Vegetated Open Channel

Fathi (1997) offered a functional relationship which is based on dimensional analysis for estimating the resistance exerted on the flow by the emergent, tall and densely vegetated channels on the flow.

$$C_d \left(\frac{A}{\forall}\right) h = Function\left(\frac{\rho U^2 y^4}{J}\right) \qquad (17)$$

Where *a*, is the horizontal area of the flow covered with vegetation; *y*, is the flow depth; ∀, is *y* times *a*, *h*, is the vegetation average height in canopy, *U* is the velocity of the flow, *A* is cross-sectional area, *J* is flexural rigidity.

Wu (1999) has assessed the flow characteristics on Rubberized horsehair mattress material in subcritical flow condition for the Froude number between 0.1- 0.4. From his experimental data, Wu plotted the relationship between C_d' and Reynold's number R_d and the obtained drag coefficient for vegetated channels in (Fig. 5).

$$C_d' = \frac{(3.44 \times 10^6) S^{0.5}}{R_d^k} \qquad (18)$$

Where, k is vegetative characteristic number.

By substituting C_d' in the n_b equation:

$$n_b = \frac{(3.44 \times 10^6)\nu}{2g}\, y^{-1/3} \qquad (19)$$

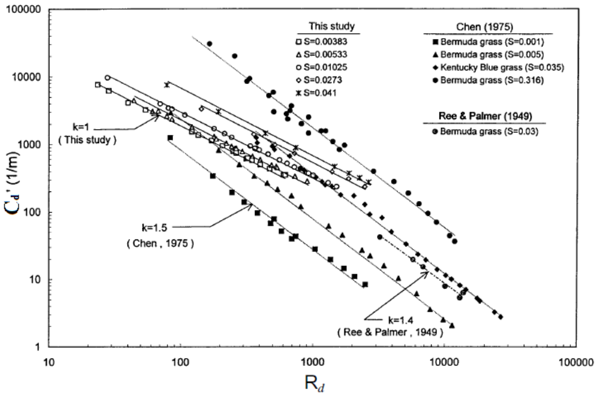


Figure 5. Relationship between vegetal drag coefficient and Reynolds number for emergent condition (Wu 1999).

Stone and Shen (2002) used also the momentum balance in the flow direction to describe the drag force in a vegetated area in open channel. However, not like other studies, the portion of the channel area that was occupied by the stems (*Φ*) was subtracted when the gravitational force per unit area was calculated:

$$\tau_G = \rho g S y\,(1 - \Phi\, l_w) \qquad (20)$$

Where l_w is wetted stem length/flow depth ratio.

and $\Phi = N\pi \frac{d^2}{4}$ is area concentration of stems (vegetation density); where N is the number of stems per unit plan area of bed; and *d* is the stem diameter.

And by considering the maximum velocity (U_c) in the stem layer, instead of the frequently used apparent vegetation layer velocity, the yielded equation of drag force per unit area is:

$$\tau_d = C_d N d \frac{\rho U_c^2}{2} \qquad (21)$$

For bed friction per unit area

$$\tau_b = \frac{\rho U_l^2 f_b}{8}(1-\Phi) \quad (22)$$

Where U_l is the average stem layer velocity and f_b is the friction factor of the channel bed.

And drag coefficient can be calculated from this equation:

$$U_l = [ySg\,(1-\Phi l_w)]^{\frac{1}{2}}\left[\frac{f_b(1-\Phi)}{8}+\left[\frac{2\Phi l_w C_d}{\pi d\left(1-\sqrt{\frac{4\Phi}{\pi}}\right)^2}\right]\right]^{\left(\frac{-1}{2}\right)} \quad (23)$$

Cheng (2013) also concluded that drag force exerted by several stems could be calculated by

$$F_d = \frac{\pi d^2}{4\lambda} \quad (24)$$

And drag coefficient can be obtained by

$$C_d = \frac{\pi}{2\lambda}\frac{gdS}{U_v^2} \quad (25)$$

Where U_v is the average flow velocity through the emergent vegetation and drag coefficient gives the same result as for the single stem in case of sparse array of stems.

Tanino and Nepf 2008, experimentally investigated the array drag where presented in the form of the array-averaged C_d and $\langle\overline{F_d}\rangle_H/(\mu U_p)$ where, $\langle\overline{F_d}\rangle_H$ = Depth-averaged of averaged drag in the direction of the average flow per unit length of stem; U_p (mean pore velocity) is the cross-sectional average of the fluid mean velocity U in control volume. Both C_d and $\langle\overline{F_d}\rangle_H/(\mu U_p)$ increase with Φ. C_d monotonically diminishes as R_d increases. The R_d dependence of $\langle\overline{F_d}\rangle_H/(\mu U_p)$ is consistent with Ergun's (1952) formulation, as was observed by Koch and Ladd (1997). Therefore, $\langle\overline{F_d}\rangle_H/(\mu U_p)$ and C_d for a given Φ can be predicted by interpolating the α_0 and α_1 values from Fig. (6) and Eq. (26), respectively, and applying them to Eqs. (27) and (28). These predictions are strictly valid only in the range $30 \le R_d \le 700$. In particular, it should be mentioned that Nepf (1999) reports the opposite Φ dependence of C_d for $R_d \ge 1{,}000$.

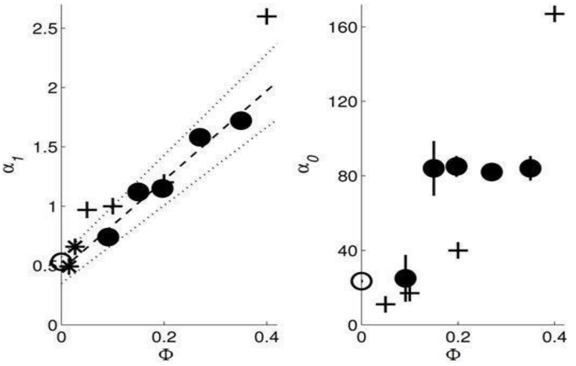
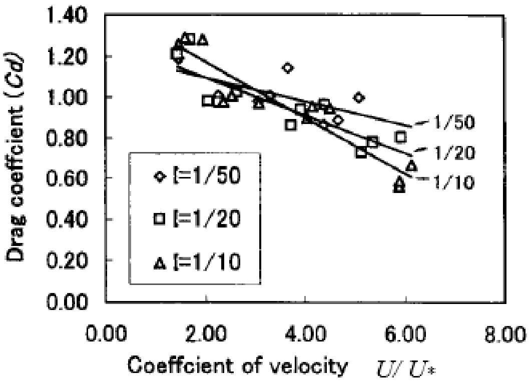


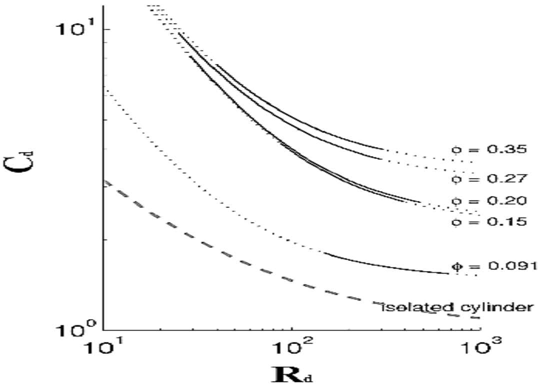
Figure 6. Scatter graph of λ versus α_0 and α_1 (Tanino, Y., & Nepf, H. M. 2008).

$$\alpha_1 = (0.46 \pm 0.11) + (3.8 \pm 0.5)\Phi \quad (26)$$

$$\frac{\langle\overline{F_d}\rangle_H}{\mu Up} = \alpha_0 + \alpha_1 R_d \quad (27)$$

$$C_d = 2\left(\frac{\alpha_0}{R_d} + \alpha_1\right) \quad (28)$$





Where α_0 and α_1 empirical coefficients, α_1 is a function of Φ and α_0 is a constant. It was observed that α_0 increases from 25±12 at Φ = 0.091 and to 84±14 at λ=0.15. However, it remains constant within uncertainty for Φ =0.15–0.35 at α_0 =83.8. By plotting the relation between C_d and R_d the following graph was obtained. (Fig. 7).

Figure 7. C_d as a function of R_d for λ =0.091, 0.15, 0.20, 0.27, and 0.35 (Tanino and Nepf (2008).

Ishikawa (2000) in case of trees (riparian) suggested the following equation to calculate the resistance force.

$$F_d = 0.78\, C_d\, \rho(\lambda_s y)^{0.06} U_* \quad (29)$$

Where U_* is the shear velocity which can be calculated from the following equation

$$\frac{U}{U_*} = 0.26\,\lambda_s^{-0.53} \quad (30)$$

Where U/U_*, is the coefficient of velocity of the flow within trees, it is presumed to signify the total resistance coefficient on the trees and channel bed. And the relationship between them depicted on figure (8).

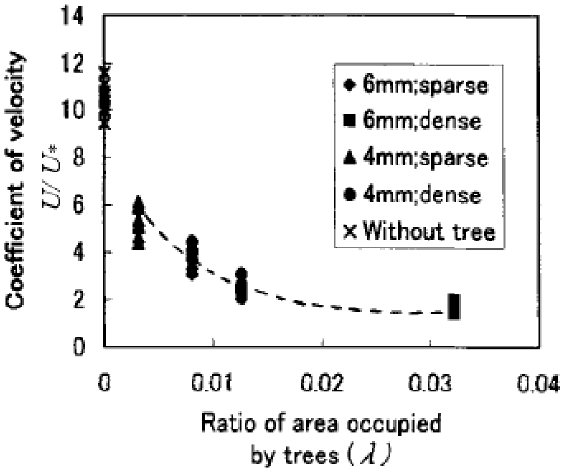


Figure 8. Relationship between coefficient of velocity, U/U_* and ratio of area occupied by trees, λ_s (Ishikawa 2000).

The relation between drag coefficient, C_d and velocity coefficient is also depicted below in Figure (9).

Figure 9. Relationship between drag coefficient, C_d and coefficient of velocity, U/U_* (Ishikawa 2000).

C. Depth Effects

Temple et al. (1987) claimed that as flow depth increases to the limit that was lower than top the vegetation the flow mean velocity changes. Consequently, flow resistance leans toward increase with the depth. Chow (1959) pointed out that the increase of Manning’s n with flow depth is normal for partly submerged vegetation lengthwise rivers with high roughness beds and banks or floodplains. Though, there has not been obvious evidence explaining that for emergent vegetation condition the change of the mean flow velocity can be ignored. (Wu 1999).

Vegetation density in wetland ecosystems and velocity are depth variable. Kadlec (1990) were measured the profile of Vegetation density for the sedge cover type at the Houghton Lake, Michigan, site. Measurements were made of leaves and stems size and number as stem density. The profile of vegetation frontal area versus size of the vegetation is shown in Fig. 10. A large frontal area in the litter layer and diminishing frontal area to zero at the top of the canopy can be observed. Leaves are thicker near their base, but litter contains fragments of all sizes. Similar depth effects have been reported by Burke and Stolzenbach (1983). The friction slope created at any depth by stem drag is related to frontal area via

$$S = C_d\, a\,\frac{u^2}{2g} = X\frac{u^2}{2g} \qquad (31)$$

Where X_f, is a local resistance coefficient which is changing with y; and u_a = $u(y)$, is the actual velocity in that stratum. The average velocity for a given slope, S and average depth, $\bar{y}$ is calculated from

$$U = \frac{1}{\bar{y}}\int_0^{\bar{y}} u(y)dy = \frac{1}{\bar{y}}\int_0^{\bar{y}} \sqrt{\frac{2gS}{X(y)}}\, dy \qquad (32)$$

Thus, if measurements are available only for the average velocity, depth, and slope, only the average value of local resistance coefficient, X may be calculated as:

$$\bar{X} = \frac{2gS}{U^2} \qquad (33)$$

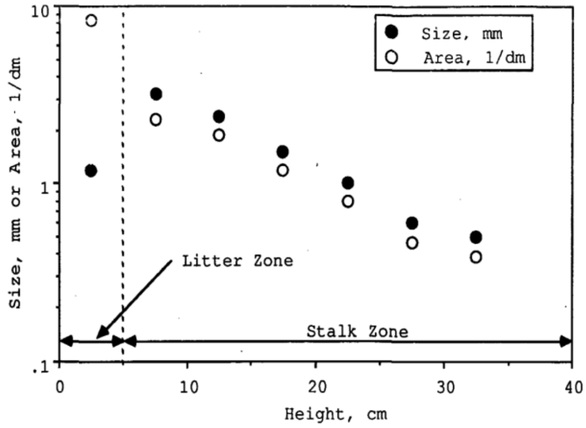


Figure 10. Vegetation frontal area per unit volume and size as function of height above ground in sedge cover type in houghton lake wetland (Kadlec 1990).

Several sets of data for X, calculated from either Eqn. (32) or (33), are depicted versus depth in Fig. 11. Over the first meter, the resistance coefficient falls exponentially at around 10 for each 30 to 40 cm augment in depth. In this work the actual functional form of the dataset was exponential. However, the logarithmic form suggested by Kouwen et al. (1969) also fits the data rationally well. Petryk and Bosmajian (1975) present correlations for X versus depth for several terrestrial ecosystems in which the lower resistance observed than the wetland systems. Other terrestrial systems have much lower resistances. Shih and Rahi (1982) showed that seasonal variations can change the resistance by an order of magnitude, with high values at the end of the growing season.

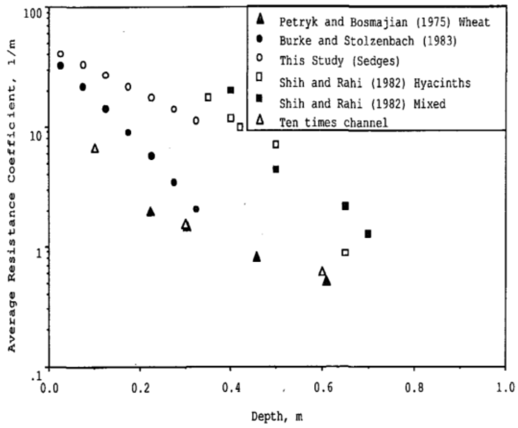


Figure 11. Different experiments' resistance coefficient versus depth (Kadlec 1990).

VI. OTHER COMBINATIONS

It is likely to deal with the transition from laminar to turbulent flow in the ways of not combining laminar and turbulent terms. Horton (1938) proposed that the friction slope be calculated from

$$S_f = kd^bU^c \qquad (34)$$

where b = zero for flow through vegetation, -2.0 for laminar flow, and -4/3 for turbulent flow; c = one for vegetated flow or laminar and two for turbulent flow; and k = a constant (different for the three cases). The value of c will be adjusted between one and two for transition flow. Friction factor correlation is another alternative instead of drag coefficient correlation. There are several versions for friction factor correlation, of which the Darcy-Weisbach definition is the most utilized one (Eq. 3).

Generally, friction factor, f is a function of depth, Reynolds number, and the friction slope. Chen (1976) provides f data for a large number of conditions for flow over grassed slopes. Correlation is with the depth Reynolds number, the slope, and the type of grass. Similar approaches have been used in other disciplines, such as the correlations of Gunter and Shaw (1945) for flow across the tube banks. The datasets indicate that wetland flows are in the transition region, either viewed from the stem Reynolds number criteria or the depth Reynolds number criteria. Chen (1976) found friction factors for grassed channels three-four orders of magnitude higher than for open channels. Petryk and Bosmajian (1975) found Manning's coefficients an order of magnitude higher for vegetated situations.

VII. APPLICATION OF KÁRMÁN VORTEX STREET IN APPROXIMATION OF DRAG AMOUNT

Takemura and Tanaka (2007) investigated the drag force effects by colony type stems with different incident velocity. The stems arrangements were in staggered and grid type, which can be observed in the Figure 12.

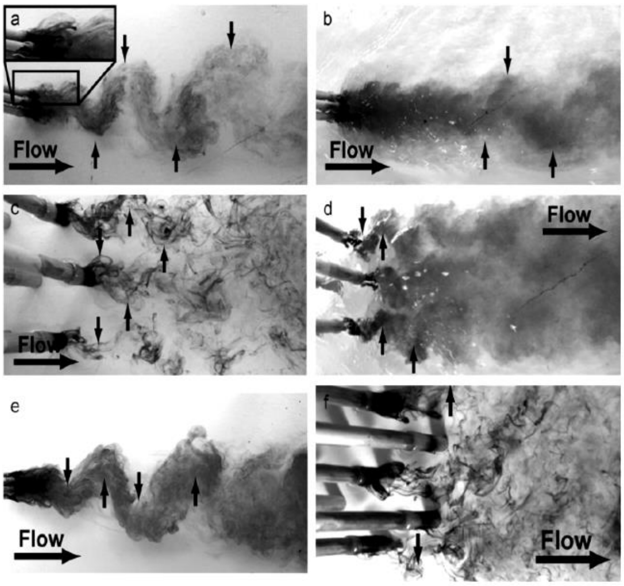


Figure 12. Pictures a, b, c and d show grid arrangement. Pictures e and d show staggered arrangement (Takemura, T., & Tanaka, N. 2007).

It can be observed in Figure (13a) that the drag force has a dissimilar augmented tendency in the two arrangements. Bokaian and Geoola (1984) reported that C_{ds} (single cylinder drag coefficient) of a backside cylinder were lesser than that of the front with around 98% coverage of C_{ds} on the front cylinder in the distance of L/d >20 when the two cylinders were arranged in a stream-wise direction. In the staggered arrangement, C_{ds} of the backside cylinder grabbed around 98% value even at the close distance of L/d =1. The spacing between cylinders in the longitudinal direction is different in both grid and staggered arrangements and it is affecting the increasing tendency of drag force. In addition, one reason for the variation in drag force is the largeness of frontal projected area in the staggered arrangement.

Figure (13b), shows the colony type drag coefficient changes with L/D. In the grid arrangement, C_{dc} (drag coefficient of the colony) is around 1 when L/d=0.25, near to the single cylinder value. C_{dc} increases with L/d but almost stays around 1.3 when L/d >1. Also, C_{dc} of the staggered arrangement diminishes around 10% with increasing L/d from 0.25 to 1 in which the backside cylinders are covered by the front-side cylinders; So, the frontal projection area augments with L/d. This reasons C_{dc} of the staggered arrangement to diminish notwithstanding the increase in drag force.

To comprehend the C_{dc} trend, the variations of C_d with L/d studied. C_d of an individual cylinder increases with L/d from 0.5 to 1. There is a significant difference in C_d. The difference diminishes with increasing L/d. The change of drag coefficient by the interaction between front-side two cylinders as a function of L/d was also confirmed by (Lam, K., Li, J.Y., Chan, K.T., So, R.M.C. 2003).

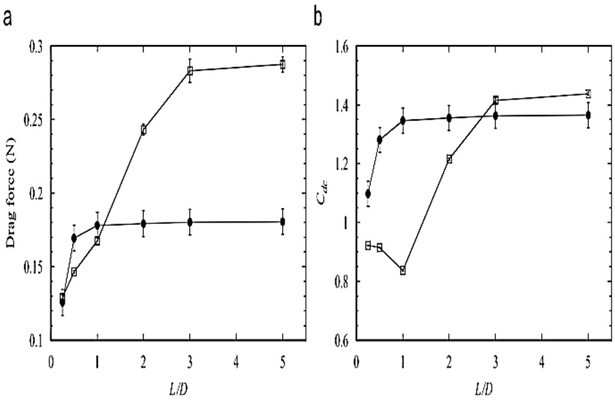


Figure 13. Relationship between L/d and drag force for colony models (with a grid arrangement or a staggered arrangement (Takemura, T., & Tanaka, N. 2007).

VIII. CONCLUSION

At low vegetation density, the flow behaves similar to the flow around an isolated cylinder, while there are significant structural differences at high cylinder density. Flow resistance increase with both density and cylinder Reynolds number (Stoesser et al., 2010).

The relationship for C_d of an emergent rigid stem in subcritical flow is proposed in equation (16). This equation yields a logic estimate of C_d for an isolated cylinder placed in channel flow (Kothyari 2009).

Froude number has little impact on C_d in subcritical flow condition, but C_d significantly diminishes as Froude number increases in supercritical condition (Kothyari 2009).

Hydraulic radius can be an important length scale in the explanation of friction factor, drag coefficient and Reynolds number for emergent vegetated open channel flow. From the experimental results, the drag coefficient diminishes with the Reynolds number independent of vegetation density (Cheng ,2011). According to Cheng (2011), Ergun equation, if apply to open channel flows through vegetation, underestimates the drag coefficients for low Reynolds numbers and coinciding overestimates the drag coefficients for high Reynolds numbers.

Both C_d and $\langle \overline{F_d} \rangle_H$ increase with λ. C_d monotonically diminishes as R_d increases. The predicted C_d for a given λ is strictly valid only in the range of $30 \leq R_d \leq 700$. In particular, it should be mentioned that Nepf (1999) reports the opposite λ dependence of C_d for $R_d \geq 1{,}000$. Additional measurements are required to determine if our results can be extrapolated to higher R_d. Similarly, the R_d dependence changes as R_d approaches 0 (Tanino and Nepf 2008).

The spacing between cylinders in the longitudinal direction is different in both grid and staggered arrangements and it is affecting the increasing tendency of the drag force. In addition, one reason for the variation in drag force is the largeness of frontal projected area in the staggered arrangement (Takemura 2007).

NOTATIONS

a	projected area of the vegetation
A	Cross-sectional area
A_m	Momentum absorption area (MAA = projection of area of leaves and stems in cross-flow direction of flow)
C	Chézy coefficient
C_d	Drag coefficient
C_{dc}	Drag coefficient of the colony type stems (cylinders)
C_{ds}	Single stem's drag coefficient
d	Diameter of one cylinder
F	Friction factor
F_d	Drag force
f_b	Friction factor of the channel bed
F_f	Bed friction force
$\langle \overline{F_d} \rangle_H$	Depth-averaged of averaged drag in the direction of the average flow per unit length of stem
g	Gravitational acceleration
G	Cross-streamline (lateral) distance between cylinders
h	Average height of the vegetation in canopy
J	Flexural rigidity
L	Channel reach distance
l_w	Wetted stem length
L	Longitudinal distance between two consecutive cylinders
n_m,	Manning's resistance coefficient
n_b	Manning's n related to bed friction
N	Number of stems per unit plan area
P_e	The wetted perimeter
q	Unit width discharge
R_d	Stem or cylinder Reynolds number
R_y,	Depth Reynolds number
S	Bed slope
S_f	Friction slope
U	Velocity of fluid in flow direction
u_a	Actual velocity in stratum ($u_a = u_a(y)$)
U_c	Maximum velocity within stem layer
U_l	Average stem layer velocity
U_p	Temporally and cross-sectionally averaged pore velocity
U_v	Average flow velocity through vegetation
U_*	Shear velocity
X_f,	Local resistance coefficient which is changing with y
y	flow depth
$\overline{\quad}$	Average operator
μ	Fluid Viscosity
λ	Vegetal area coefficient = area fraction per unit length
λ_s	Ratio of occupied area by tree $(\pi d^2/4L^2)$
$\forall$	Canopy volume

Φ	Cylinder volume fraction (= vegetation density)
τ_b	Bed friction per unit area
τ_d	Drag force per unit area
τ_G	Gravitational force per unit area

REFERENCES

[1] Arcement, G. J., & Schneider, V. R. "Guide for selecting manning's roughness coefficients for natural channels and flood plains." *US Government Printing Office.*, 1989.

[2] Baptist, M. J. "Modelling floodplain biogeomorphology TU Delft,." *Delft University of Technology*, 2005.

[3] Bennett, C. O., and Myers, J. E. *Momentum, heat and mass transfer.* New York, N.Y.: McGraw-Hill, 1982.

[4] Bokaian, A., Geoola, F. "Wake-induced galloping of two interfering circular cylinders." *J. Fluid Mech.* 146 (1984): 383–415.

[5] Burke, R. W., & Stolzenbach, K. D. . "Free surface flow through salt marsh grass ." 1983.

[6] Chen, C. "Flow resistance in broad shallow grassed channels." *J. Hydr. Div., ASCE* 102, no. 3 (1976): 307-322.

[7] Cheng, N. "Calculation of drag coefficient for arrays of emergent circular cylinders with pseudofluid model. ." (Journal of Hydraulic Engineering) 139, no. 6 (2013): 602-611.

[8] Cheng, N., & Nguyen, H. T. "Hydraulic radius for evaluating resistance induced by simulated emergent vegetation in open-channel flows." *Journal of Hydraulic Engineering* 137, no. 9 (2011): 995-1004.

[9] Chou, P. Y. "On the velocity correlations and the solution of the equations of turbulent fluctuation." *Quart. Appl. Math*, 1945: 3-38.

[10] Chow, V. T. "Frequency analysis of hydrologic data with special application to rainfall intensities ." *University of Illinois Engineering Experiment Station*, 1953: 414.

[11] Ergun, S. "Fluid flow through packed columns." *Chem. Eng. Prog*, 1952: 48.

[12] Fathi-Moghadam, M., & Kouwen, N. "Nonrigid, nonsubmerged, vegetative roughness on floodplains." *Journal of Hydraulic Engineering*, 1997.

[13] Fenzl, R. N. "Hydraulic Resistance of Broad Shallow Vegetated Channels." 1962.

[14] Ferguson, R. "Time to abandon the manning equation?" *Earth Surface Processes and Landforms* 35, no. 15 (2010): 1873-1876.

[15] Finn, R. K. "Determination of the drag on a cylinder at low Reynolds numbers." *J. Appl. Phys.* 24, no. 6 (1953): 771–773.

[16] Galema, A. *Vegetation resistance evaluation of vegetation resistance descriptors for flood management.* 2009.

[17] Gu, F., Ni, H., & Qi, D. "Roughness coefficient for unsubmerged and submerged reed." *Journal of Hydrodynamics* (Ser.B) 19, no. 4 (2007): 421-428.

[18] Gunter, A. Y., and Shaw, W. A. "A general correlation of friction factors for various types of surfaces in crossflow." *Trans., Am. Soc. of Mech. Engrs.* 67 (1945): 643-660.

[19] Haslam, S. M., & Wolseley, P. A. "River vegetation, its identification, assessment, and management: A field guide to the macrophytic vegetation of british watercourses CUP Archive ." 1981.

[20] Horton, R. E. "The interpretation and application of runoff plat experiments with reference to soil erosion problems." *Proc, Soil Sci. Soc. of America* 3 (1938): 340-349.

[21] Ishikawa, Y., Mizuhara, K., & Ashida, S. . "Effect of density of trees on drag exerted on trees in river channels." *Journal of Forest Research* 5, no. 4 (2000): 271-279.

[22] James, C., Birkhead, A., Jordanova, A., & O'sullivan, J. "Flow resistance of emergent vegetation." *Journal of Hydraulic Research* 42, no. 4 (2004): 390-398.

[23] Järvelä, J. "Determination of flow resistance caused by non-submerged woody vegetation." *International Journal of River Basin Management* 2, no. 1 (2004): 61-70.

[24] Jayaweera, K. O. L. F., and Mason, B. J. "The behaviour of freely falling cylinders and cones in a viscous fluid." *J. Fluid Mech* 22, no. 4 (1965): 709–720.

[25] Jordanova, A. A., & James, C. "Experimental study of bed load transport through emergent vegetation." *Journal of Hydraulic Engineering* 129, no. 6 (2003): 474-478.

[26] Kadlec, R. H. "Overland flow in wetlands: Vegetation resistance." *Journal of Hydraulic Engineering* 116, no. 5 (1990): 691-706.

[27] Kao, D. T., & Barfield, B. J. "Prediction of flow hydraulics for vegetated channels." *Transactions of the*

ASAE [American Society of Agricultural Engineers], 1978.

[28] Kim, S. J., & Stoesser, T. "Closure modeling and direct simulation of vegetation drag in flow through emergent vegetation." *Water Resources Research* 47, no. 10 (2011).

[29] Klaassen, G., & Van der Zwaard, J. "Roughness coefficients of vegetated flood plains." *Journal of Hydraulic Research* 12, no. 1 (1974): 43-63.

[30] Koch, D. L., and Ladd, A. J. C. "Moderate Reynolds number flows through periodic and random arrays of aligned cylinders." *J. Fluid Mech* 349 (1997): 31–66.

[31] Kothyari, U. C., Hayashi, K., & Hashimoto, H. "Drag coefficient of unsubmerged rigid vegetation stems in open channel flows." *Journal of Hydraulic Research* 47, no. 6 (2009): 691-699.

[32] Kouwen, N., & Fathi-Moghadam, M. . "Friction factors for coniferous trees along rivers." *Journal of Hydraulic Engineering*, 2000.

[33] Kouwen, N., & Moghadam, F. . "Friction factor for vegetation." *2nd Symposium on Habitat Hydraulics.* Quebec: Proc, 1996. 251-A257.

[34] Kundu, P. K., Cohen, I. M., and Hu, H. H. *Fluid mechanics.* Amsterdam, The Netherlands: Elsevier Academic, 2004.

[35] Lam, K., Li, J.Y., Chan, K.T., So, R.M.C. "Flow pattern and velocity field distribution of cross-flow around four cylinders in a square configuration at a low Reynolds number." *J. Fluids Struct* 17 (2003): 665-679.

[36] Lee, J. K., Roig, L. C., Jenter, H. L., & Visser, H. M. . "Drag coefficients for modeling flow through emergent vegetation in the florida everglades ." *Ecological Engineering* 22, no. 4 (2004): 237-248.

[37] Li, R., & Shen, H. W. . "Effect of tall vegetations on flow and sediment." *Journal of the Hydraulics Division* 99, no. 5 (1973): 793-814.

[38] Liu, D., Diplas, P., Fairbanks, J., & Hodges, C. "An experimental study of flow through rigid vegetation." *Journal of Geophysical Research: Earth Surface (2003–2012)* 113, no. F4 (2008).

[39] López, F., & García, M. . "Open-channel flow through simulated vegetation: Suspended sediment transport modeling." *Water Resources Research* 34, no. 9 (1998): 2341-2352.

[40] Naot, D., Nezu, I., & Nakagawa, H. "Hydrodynamic behavior of partly vegetated open channels." *Journal of Hydraulic Engineering* 122, no. 11 (1996): 625-633.

[41] Nehal, L., & Ming, Y. Z. . "Study on the flow of water through non-submerged vegetation ." 2005.

[42] Nepf, H. "Drag, turbulence, and diffusion in flow through emergent vegetation." *Water Resources Research* 35 , no. 2 (1999): 479-489.

[43] Nepf, H., & Vivoni, E. "Drag and diffusivity within emergent vegetation. Bridges." 10, no. 40382 (1998): 8.

[44] Niemann, H. J., and Holscher, N. "A review of recent experiments on the flow past circular cylinders." *J. Wind Eng. Ind. Aerodyn* 33, no. (1–2) (1990): 197–209.

[45] Oliver, H. "Wind profiles in and above a forest canopy." *Quarterly Journal of the Royal Meteorological Society* 97 , no. 414 (1971): 548-553.

[46] Petryk, S., & Bosmajian, G. . "Analysis of flow through vegetation." *Journal of the Hydraulics Division* 101, no. 7 (1975): 871-884.

[47] Powell, D. M. "Flow resistance in gravel-bed rivers: Progress in research." *Earth-Science Reviews* 136 (2014): 301-338.

[48] Ree, w. o., & Palmer, V. J. "Flow of water in channels protected by vegetative linings." (U.S. Dept. of Agriculture) 1945: 115 pages.

[49] SALVADOR, G. P., STOESSER, T., RUMMEL, A. C., & RODI, W. "Turbulent shallow flow through vegetation." *Paper presented at the Fifth International Symposium on Environmental Hydraulics (ISEH V), .* 2007.

[50] Shaw, R.H., G. den Hartog, K.M. King, and G.W. Thurtell, . "Measurements of mean wind flow and three-dimensional turbulenceintensity within a mature corn crop." *Agric. Meteorology*, 1974: 13:419-425.

[51] Shi, Z., Pethick, J., & Pye, K. "Flow structure in and above the various heights of a saltmarsh canopy: A laboratory flume study." *Journal of Coastal Research*, 1995: 1204-1209.

[52] Stoesser, T., Kim, S., & Diplas, P. "Turbulent flow through idealized emergent vegetation." *Journal of Hydraulic Engineering*, 2010.

[53] Stone, B. M., & Shen, H. T. "Hydraulic resistance of flow in channels with cylindrical roughness." *Journal of Hydraulic Engineering* 128 , no. 5 (2002): 500-506.

[54] Suzuki, T., & Arikawa, T. "Numerical analysis of bulk drag coefficient in dense vegetation by immersed boundary method." *Paper presented atthe Proceedings of the 32nd International Conference on Coastal Engineering, ICCE.* June/July, Shanghai,, 2010.

[55] Takemura, T., & Tanaka, N. "Flow structures and drag characteristics of a colony-type emergent roughness model mounted on a flat plate in uniform flow." *Fluid Dynamics Research* 39, no. 9 (2007): 694-710.

[56] Tanino, Y., & Nepf, H. M. . "Laboratory investigation of mean drag in a random array of rigid, emergent cylinders." *Journal of Hydraulic Engineering*, 2008.

[57] Te Chow, V. *Open channel hydraulics.* New York: McGraw-Hill Book Company, Inc, 1959.

[58] Temple, D., Robinson, K. M., Ahring, R. M., & Davis, A. G. *Stability design of grass-lined open channels.* United States Department of Agriculture. (Agriculture Handbook Number 667), Agricultural Research Services, 1987.

[59] Thom, A. "Momentum absorption by vegetation." *Quarterly Journal of the Royal Meteorological Society* 97, no. 414 (1971): 414-428.

[60] Thompson, G. T., & Roberson, J. A. "A theory of flow resistance for vegetated channels." *Transactions of the ASAE*, 1976.

[61] Tritton, D. J. "Experiments on the flow past a circular cylinder at low Reynolds numbers." *J. Fluid Mech.* 6, no. 4 (1959): 547–567.

[62] Tsujimoto, T. "Appearance of organized fluctuations in open-channel flow with vegetated zone ." *KHL Commun* 3 (1992): 37-45.

[63] Turner, A., & Chanmeesri, N. "Shallow flow of water through non-submerged vegetation." *Agricultural Water Management* 8, no. 4 (1984): 375-385.

[64] Wieselsberger, C. "New data on the laws of fluid resistance."Technical note No. 84"." *National Advisory Committee for Aeronautics*, 1922.

[65] Williamson, C. H. K. "Vortex dynamics in the cylinder wake." *Annu. Rev. Fluid Mech.* 28, no. 1 (1996): 477–539.

[66] WU, F. "Characteristics of flow resistance in open channels with non-submerged rigid vegetation." *Journal of Hydrodynamics* (Ser.B) 20, no. 2 (2008): 239-245.

[67] Wu, F., Shen, H. W., & Chou, Y. . "Variation of roughness coefficients for unsubmerged and submerged vegetation." *Journal of Hydraulic Engineering*, 1999.

[68] Yen, B. C. "Open channel flow resistance. Journal of Hydraulic Engineering." 128, no. 1 (2002): 20-39.

[69] Zdravkovich, M. M. *Flowaroundcircular cylinders:Acomprehensive guide through flow phenomena, experiments, applications, mathematical models, and computer simulations.* Oxford, UK: Oxford University Press, 1997.

[70] Zhao, K., Cheng, N., Wang, X., & Tan, S. K. . "Measurements of fluctuation in drag acting on rigid cylinder array in open channel flow." *Journal of Hydraulic Engineering* 140, no. 1 (2013): 48-55.