HYDRAULIC MODELING OF A NATURE-BASED APPROACH TO SUBMERGED FLEXIBLE DRAINAGE LINING

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ABSTRACT

This study applies dimensional analysis to the hydrodynamics of vegetative channels. It further uses in –house one-dimensional (1-D) hydrodynamic model to replicate velocity profiles obtained from several laboratory experiments under varying hydraulic conditions and flexibilities. Based on the dimensionally scaled vegetative and flow parameters, the results show that velocity profiles, Reynolds stresses and deflected height of vegetation depends on the flow conditions and plant flexibility.

Keywords: Hydraulic roughness equation, velocity profile, 1-D model, dimensional analysis, flexible lining.

1. Introduction

Natural river channels and wetlands have ecological importance in riverine landscapes (Newson, 1992; Ward *et.al,* 2001). Vegetation around the channels comprises a diverse and heterogeneous combination of herbs, shrubs and trees, which influence sediment, nutrient and pollutant transport (Nepf and Vivoni, 2000). Vegetation also reduces erosion and flooding because the velocity of flow in the vegetation zone of a drainage channel decreases with density. Two types of vegetation are usually defined: stiff (typically woody) and flexible (herbaceous plants).

Flexible herbaceous vegetation is widely used as a protective liner in agricultural waterways, flood channels or drainages. Effects of vegetation on flow are important and could cause difficulties in hydraulic design. Submerged conditions are distinguished, since flow phenomena become more complicated when the flow depth exceeds the height of plants.

The purpose of this paper is to use a hydrodynamic model to replicate velocity profiles, Reynold stresses and deflection obtained from several laboratory Experiments under varying hydraulic conditions of flow and flexibilities.

In Nigeria, a large number of people live in places where there are river channel and streams mainly because of farming occupation, so in the past for a long period of time, the flood discharge capacity of rivers was considered as the most important factor in the river management. In recent time, increasing in flooding has resulted to loss of lives and properties. Preventing flood could save large number of lives and economic losses can also be avoided. Therefore, flexible vegetation lining should be encouraged to be planted along water way or channel. The flexible linings on natural channel dissipate the energy and the velocity of the flow. So it is advisable to rebuild a healthy aquatic ecosystem. A great effort should be made to recover the healthy ecological environment of rivers and riparian zones. This paper presents a numerical model to replicate the hydraulic behaviour of a natural-based canopy along waterways.

The restoration of natural riverine environment is a significant task in river management worldwide. This prompts the hydraulic research in vegetated flows in streams, rivers and coastal waters. Vegetation is an indicator of richness and diverse living resources with possession of great environmental and socio-economic importance for many countries of the world (DSD/ Moc MacDonald, 2009). The growth of natural vegetation in waterway and wetlands is favoured because of its ecological and environmental importance (Lopez and Garcia, 2001; Li and Yu, 2010). Vegetation can trap and stabilize sediment along waterways as well as to reduce river bed erosion (Wilson, 2007).

In addition, it can improve water quality, reduce turbidity, induces biological purification processes, hence reduce discharged nitrates and phosphates in rivers (Velasco et al, 2003; Nezu and Sanjou, 2008). It can also attenuate flood waves and protect coastal and riparian against flooding (Cheng and Nguyen, 2011, Busari and Li, 2014); provide habitat resources and river aesthetics (Pirim et al, 2000; Li and Yan, 2007); balance the global ecosystem (Vassilios, 2000), and enhance ecological equilibrium (Defina and Bixio, 2005). Lastly, it can provide a source of livelihood for aquatic animals (Li and Xie, 2011) and interestingly, a valuable resource for public environmental education and scientific research (DSD/ Moc MacDonald, 2009). Therefore, the understanding of the hydrodynamics of vegetation for ecological and environmental sustainability is paramount.

3. Methodology

In this study the 1-D version of the model developed by Busari and Li, 2015 is used, in most cases, vegetated flows are unidirectional and, with shallow flow depth. Multi-dimensional models require more computational effort and are not efficient for the generation of a large number of synthetic data.

3.1 Governing equations

The primary quantities to describe an open-channel flow are the velocity and pressure. For water (a Newtonian fluid), the flow is incompressible and is governed by the Navier –Stokes equations (NSE). The 1D version of the equations can be written as follows.

Continuity equation

$$\frac{\partial u_i}{\partial x_i} = 0 \qquad i{=}1 \tag{1}$$

Momentum equation in horizontal direction:

$$\frac{\partial u_i}{\partial t} + u_j\frac{\partial u_i}{\partial x_j} = \frac{\partial}{\partial x_j}\left[v_m\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) + \frac{\tau_{ij}}{\rho}\right] - \frac{1}{\rho}\frac{\partial p}{\partial x_i} - \frac{1}{\rho}F_i + g_i \qquad i{=}1, j{=}3 \tag{2}$$

where x_i $(= x_1)$ = coordinate in horizontal direction *(m)*; u_i $(= u_1)$ = time averaged velocity in horizontal direction *(m/s)*; u_j= 0; t = time (*s*); ρ = fluid density *(kg/m³)*; v_m = molecular viscosity (m^2s^{-1}); $\tau_{ij} = -\rho u_i' u_j'$ = Reynolds stresses (N/m^2); p = pressure (N/m^2) is assumed to be a constant; $F_i = F_x$ (N/m^3) is the resistance force components per unit volume induced by vegetation in *x* directions. g_i = is the x-component of the gravitational acceleration and is set to gS_0, where S_0 = channel bottom slope.

The Reynolds stresses are represented by eddy viscosity model:

$$\frac{\tau_{ij}}{\rho} = -\overline{u_i u_j} = -2v_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\delta_{ij}k \qquad i{=}1, j{=}3 \tag{3}$$

where $k = {}^1\!/_2\, \overline{u_i' u_i'}$= turbulent kinetic energy (m^2s^{-2}) which can be absorbed into the pressure gradient term and v_t = eddy viscosity (m^2s^{-1}).

The eddy viscosity v_t is specified by the Spalart-Allmaras (SA) turbulence model which involves the solution of a new eddy viscosity variable, ν. The version of the model used is for near-wall region and moderate Reynolds number, which is most relevant to the present problem (Spalart and Allmaras, 1994).

3.2 Closure model

The Spalart- Allmaras (S-A) one equation turbulence model is simpler compared to the well-known $k-\varepsilon$ model and has been found successful in the modeling of vegetated flows (Li and Yan, 2007; Li and Yu, 2010; Li and Zhang, 2010; Paul et al, 2014). The model is applicable to near–wall region and for moderate Reynolds number. It describes the convective transport, along with the production, diffusion, and destruction of eddy viscosity. Detail of the closure model can be found in (Spalart and Allmaras, 1994; Sebastien et al, 2002; Li and Yan 2007; Li and Zeng, 2009; Busari and Li, 2015).

$$\frac{\partial v}{\partial t}+u_j\frac{\partial v}{\partial x_j}=C_{b1}\tilde{S}_v v+\frac{1}{\rho}\left\{\frac{\partial}{\partial x_j}\left[(v+v_m)\left(\frac{\partial v}{\partial x_j}\right)\right]+C_{b1}\left(\frac{\partial v}{\partial x_j}\frac{\partial v}{\partial x_j}\right)\right\}-C_{w1}f_w\left(\frac{v}{d}\right)^2 \quad (4)$$

The eddy viscosity is defined as

$$\mu_t=\rho v f_{v1}=\rho v_t \quad (5)$$

Where $f_{v1}=\frac{\chi^3}{\chi^3+C_{v1}^3}$

with $\chi=\frac{v}{v_m}$ **(6)**

The vorticity magnitude S_v is modified as:

$$\tilde{S}_v=S_v+\frac{v}{\kappa^2 d^2}f_{v2}$$

with $S_v=\sqrt{\omega_j\omega_j}$ **(7)**

$$f_{v2}=1-\frac{\chi}{1+\chi f_{v1}} \quad (8)$$

$$f_w=g\left[\frac{1+C_w^6}{g^6+C_w^6}\right]^{1/6} \text{ with } g=r+C_{w2}(r^6-r), \quad r=\frac{v}{\tilde{S}_v\kappa^2 d^2} \quad (9)$$

Constants of the model are:

$\kappa = 0.41$; $\sigma = 2/3$; $C_{b1} = 0.1355$; $C_{b2} = 0.622$, $C_{v1} = 7.1$; $C_{w1} = \frac{C_{b1}}{\kappa^2} + \frac{1+C_{b2}}{\sigma}$; $C_{w2} = 0.3$; $C_{w3} = 2$ *and* d =length scale.

The S-A closure model has been basically developed for aerodynamic flows. It is intrinsically a transport equation for the eddy viscosity was developed under the well-known Boussinesq hypothesis. It has been successfully applied in the modelling of free-shear flow, wall-bound flow and separated flow problems.

The resistance force due to vegetation is defined by the quadratic friction law. The average force per unit volume within the vegetation domain is given by:

$$f_i = \frac{1}{2}\rho C_d w u_i \sqrt{u_j u_j} \quad i=1 \tag{10}$$

Where C_d = drag coefficient of stem, w = width of stem. The drag force resulted from wake formation downstream of the stem. The average force per unit volume within the vegetation domain is obtained by

$$F_i = N f_i = \frac{1}{2}\rho C_d N w u_i \sqrt{u_i u_j}$$

$$= \frac{1}{2}\rho f_{rk} u_i \sqrt{u_j u_j} \quad i=1 \tag{11}$$

where N = vegetation density (defined as number of stems per unit area, $1/\mathrm{m}^2$) and $f_{rk} = C_d N w$.

In case of wall bounded shear flow, the turbulence length scale d is proportional to the distance from the point of interest to the channel bed. In the presence of vegetation, the turbulence eddies above the vegetation layer may not reach the channel bed, thus there will be reduction in the turbulence length scale. One approach to simulate the reduction in the turbulence length scale is to introduce a zero plane displacement parameter, Z_o. The turbulence length scale of a point at level Z is obtained by

$$\begin{cases} L = Z - Z_o, & Z > h_d > Z_o \\ L = Z\,(h_d - Z_o)/h_d, & Z < h_d \end{cases} \tag{12}$$

where h_d is the deflected height of vegetation (m).

3.3 Flexibility (Large deflection analysis)

Natural vegetation bend easily in high flow and the deformation of the top of vegetation can be of the same order as the deflected plant height. Hence, the classical analytical expression for transducer deformation which is based on theory small deformation as previously used (Kutija and Hong, 1996; Erduran and Kutija, 2003; Kubrak, et al, 2008) may not be adequate for vegetation with high flexibility. The selected model uses a large deflection analysis based on the Euler-Bernoulli law for bending of a slender transducer has been used to determine the large deflection of plant stem (Li and Xie, 2011).

In the analysis each vegetation stem is modelled as a vertical in-extensible non-prismatic slender transducer of length, l. The water flows produce variable distributed loads $q_x(s)$ on the transducer along the *x*-direction as shown in Figure (1). From Euler-Bernoulli law, the local bending moment is proportional to the local curvature.

$$M(s) = EI(s)\frac{\frac{d^2\delta}{ds^2}}{1-\left(\frac{d\delta}{ds}\right)^2} \tag{13}$$

where, *M* is the bending moment (*Nm*), *s* is the local ordinate along the transducer, *E* is the modulus of elasticity (*N/m*^{2}), *I* is the Second moment of area (m^4) and, δ is the deflection in *x*-direction (*m*).

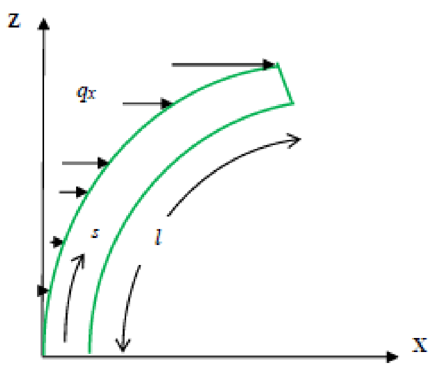


Figure 1: Schematic diagram of large deflection of a transducer carrying distributed load.

The equilibrium of forces and momentum gives

$$\frac{d^2M}{ds^2} + \frac{dM}{ds}\frac{\frac{d\delta d^2\delta}{ds\,ds^2}}{\left[1-\left(\frac{d\delta}{ds}\right)^2\right]} = -q_x(s)\sqrt{1-\left(\frac{d\delta}{ds}\right)^2} \qquad \textbf{(14)}$$

Combining of equations the Euler-Bernoulli law (13) and the equation of equilibrium of forces and moments (14) yielded a fourth order nonlinear equation in the deflection δ

$$\frac{d^2}{ds^2}\left[EI(s)\frac{\frac{d^2\delta}{ds^2}}{1-\left(\frac{d\delta}{ds}\right)^2}\right] + \frac{d}{ds}\left[EI(s)\frac{\frac{d^2\delta}{ds^2}}{1-\left(\frac{d\delta}{ds}\right)^2}\right]\frac{\frac{d\delta d^2\delta}{ds\,ds^2}}{\left[1-\left(\frac{d\delta}{ds}\right)^2\right]} = -q_x(s)\sqrt{1-\left(\frac{d\delta}{ds}\right)^2} \qquad \textbf{(15)}$$

The vegetation stem is taken as inextensible as the total length remains constant. By dividing the stem into n equal part of constant length Δs, the z-ordinate of the ith node is obtained by

$$z_i = \sum_{j=1}^{i}\sqrt{\Delta s^2 - (\delta_i - \delta_{i-1})^2} \qquad \textbf{(16)}$$

3.4 Numerical methods and Boundary conditions

The deflected height of the stem is then equal to z_n. The equation (15) is then solved using a quasi-linearized central finite difference scheme. In order to minimize computational effort, the solution is expressed in non-dimensional form relating the deflected height of vegetation to the applied force, and is approximated by a polynomial.

At the free surface, by neglecting the wind and surface tension, the dynamic condition can be satisfied by specifying zero pressure and zero gradients of velocity component:

$$p = 0 \quad and \quad \frac{\partial u_i}{\partial \sigma} = 0 \qquad \textbf{(17)}$$

At the bottom, the logarithmic law wall function is imposed to calculate the wall shear stress used in diffusion step. The wall function is given by

$$u = u_w\left[\frac{1}{\kappa}ln\left(\frac{u_w z}{v_m}\right) + B\right],$$

$$v = \kappa\, z\, u_w \qquad \textbf{(18)}$$

where u_w = wall shear velocity (m/s); z = distance from the wall (m); and $B = 8.5$. By knowing the velocity at the point next to the wall with distance, z the wall shear stress can be computed iteratively. A detailed description of the model can be found in (Busari and Li, 2015)

3. *Results and discussion*

3.5 Model Calibration

The number of (uniform) grids used is 81 and the time step size is in the order of 0.005s to ensure computational stability. Grid convergence study shows that further reduction of grid size does not affect the results practically. The 1-D model has been calibrated using data from previous experimental works conducted to investigate open channel flows with flexible or rigid submerged vegetation and the details of each laboratory investigation have been described (Busari and Li, 2016).

The following experimental cases were simulated using the model. Generally, the dataset contains eight variables, i.e., flow depth (h), energy slope (S), strip width or stem diameter (w), vegetation height (h_v), discharge (Q), flexural rigidity (EI) and number of strips or stems per unit area (N). Two parameters are required to be calibrated: the bulk drag coefficient and the zero-plane displacement parameter. The latter is significant in the clear water zone while the former is important in the vegetation zone.

Table 1: Experimental conditions (Dunn et al, 1996)

Experimental nbr.	***N*** *(stems/ m²)*	***H*** *(m)*	*h_v (m)*	***Q*** *(m^3/s)*	***S*** *(%)*
2	172	0.23	0.1175	0.088	0.36
6	43	0.27	0.1175	0.178	0.36
13	172	0.37	0.152	0.179	0.36
15	43	0.26	0.132	0.179	0.36

The experiments consisted of flows through both flexible and rigid vegetation in a flume under uniform flow conditions. Detail can be found in Dunn et al, 1996. The hydraulic conditions are as shown in Table 1. Figures 2 and 3 showed that the numerical results match well with the experimental results.

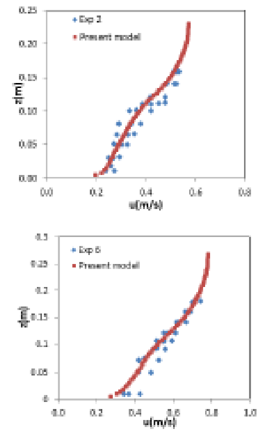


Figure 2: Comparison between computed results and measured mean vertical velocity distribution for flexible vegetation (Data from Dunn et al, 1996)

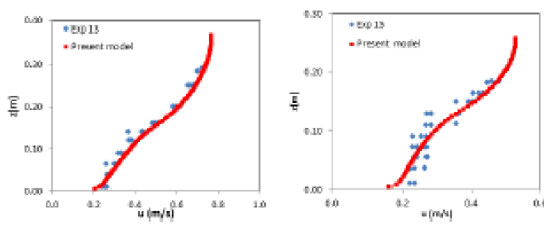


Figure 3: Comparison between computed and measured mean vertical velocity distribution for rigid vegetation. (Data from Dunn et al, 1996)

3.6 Numerical simulation

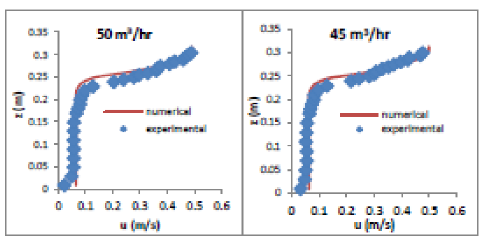
The Reynolds Averaging Navier – Stokes (RANS) model described in section (3.1) was used to simulate the flume experiments. A total of 12 simulations were shown under different hydraulic conditions using measured bulk drag coefficient. Five scenarios are presented in this paper. The key parameters are shown in Table 2. The exercise is to assess the accuracy of the S-A model to replicate the mean stream-wise fully developed vertical velocity profiles through and above vegetation patches of different areal densities as well as Reynolds stresses.

Table 2: Experimental hydraulic conditions and measured C_d' (sheltering effect)

λ (m^{-1})	h (m)	U (m/s)	f_{rk} (m^{-1})	f_v $(-)$	z_o/h_v $(-)$	gS_w (m/s^2)	C_d' $(-)$
12	0.283	0.10	46.65	11.6	0.900	0.054	3.8
24	0.318	0.15	99.68	23.8	0.937	0.010	4.1
48	0.312	0.14	120.53	30.1	0.946	0.013	2.5
48	0.319	0.16	131.17	32.8	0.949	0.017	2.7
72	0.357	0.13	131.51	32.9	0.949	0.022	1.8

Note: *S_w is the average water surface slope*

The numerical model is used to replicate all the experimental dataset. Generally, the predictions are quite good. Figures 4 and 5 are representative results, showing the comparison between the numerical results and the experimental results of the velocity profiles and Reynolds stresses obtained in this study.



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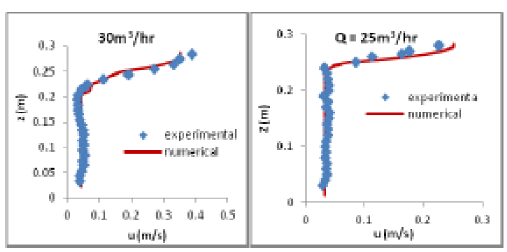

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Figure 4: Comparison of vertical distribution of mean stream-wise velocity at various flow rates for varying vegetation densities.

The computed velocity profiles agree well with those measured in the experiments. From the Figure 4, it can be seen that the numerical model successfully replicate most of the characteristics of the flows.

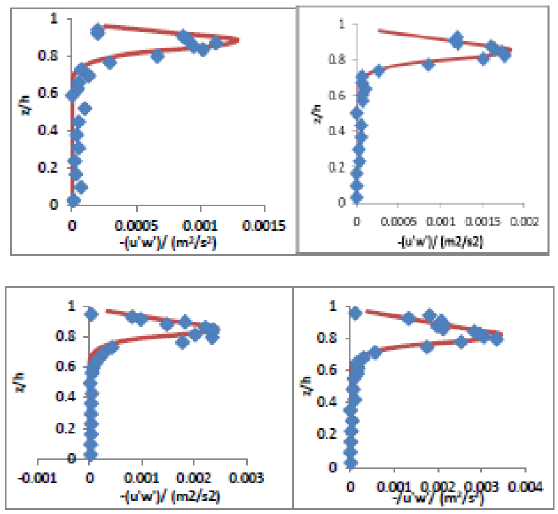

Figure 5: Comparison of vertical distribution of the Reynolds shear stresses

From the second-order velocity fluctuations u' and w', in the longitudinal and vertical directions x and z, respectively, the Reynolds stress has been calculated for the measurement under varying hydraulic conditions. In Figures 5, the predictive capability of the numerical model is further examined by simulating part of the experimentally measured vertical profiles of the Reynolds Shear stress. The Figures 5 illustrate the comparison of the measured vertical profiles of the Reynolds shear stresses and the computed one for the channeling effect under different flow condition and vegetation densities. The model predicts the maximum Reynolds stress quite well.

4. Conclusion

The hydrodynamic model has been used to simulate a vegetated open channel flow and the computed result shows that the increase in vegetation density reduces turbulence of the flow. The numerical model used to replicate all the experimental data are good. The comparison between the numerical result and Experimental results of the velocity profile and Reynold shear stresses obtained in this study are good in agreement. The mean vertical velocity distribution profiles and Average Reynolds stresses are well predicted using the 1-D RANS model. The understanding of vegetation for Ecological and Environmental sustainability is important. Restoration of natural riverine and Environment is important task in water channel or river management worldwide.

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