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Effect of rigid, bank vegetation on velocity distribution and water surface profile in open channel

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ABSTRACT

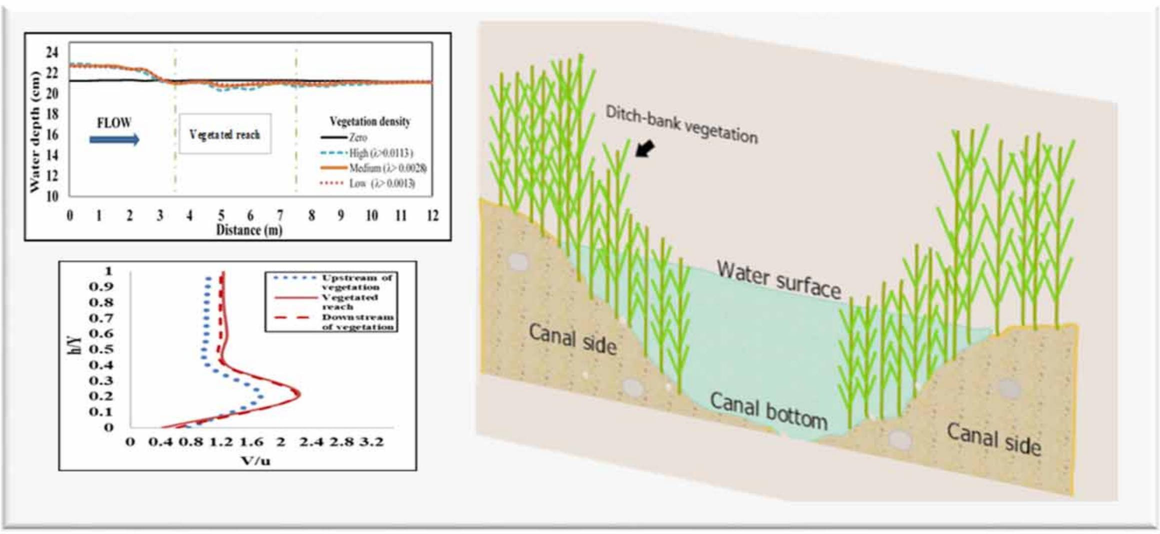
The effects of rigid ditch bank vegetation on velocity distribution and water surface profile in trapezoidal open channels were investigated. Forty-eight tests were used to study the impacts of different vegetation densities. Tests were run for three vegetation densities (1,600, 400, and 178 stems/m^2) along a fixed, 4.00 m reach, against four different discharges, each with three different depths. The measured water levels and velocities were analyzed and it was found that increasing the vegetation density increased the water depth upstream of the vegetated reach. while lowering it within it, when compared to the unvegetated case. The water's velocity profile as a ratio to the unvegetated case (V/u) is sigmoid, i.e., the maximum velocity $(V/u)_{max}$ occurs in the lower half of the water column, increasing shear stress near the bed, and, in turn, the likelihood of bed erosion along the vegetated channel's centerline. V/u increased with increasing vegetation density and Fr_o. A multiple regression analysis was done to assess the impact of ditch bank vegetation density on flow parameters.

Key words: density, empirical equations, rigid ditch bank vegetation, velocity distribution, water profile

HIGHLIGHTS

- The study examines the hydraulic issues that may arise in trapezoid open channels due to the presence of vegetation on its sides slopes.
- The presence of vegetation changes water levels and increases velocity near the bed which increases the possibility of bed erosion.

GRAPHICAL ABSTRACT



MATHEMATICAL SYMBOLS

Y Water depth (m);
Y_o Water depth in the unvegetated case (m);
Y_{in} Average water depth in the vegetated reach (m);
h Vertical height of the measured velocity point above the bed (m);
V Water velocity in the vegetated case (m/s);
u Water velocity in the unvegetated case (m/s);
V_{in} Water velocity in the middle of the vegetated reach (m/s);
$\overline{u}$ Average flow velocity in the unvegetated case (m/s);
Fr_o Froude number in the unvegetated case.
g Gravitational acceleration (m/s^2);
λ Vegetation density ($\lambda = \Pi N^0 d^2/4$, where N^0 is the number of stems per unit bank area and d the stem diameter (m), and
Q Discharge (l/s).

1. INTRODUCTION

Ditch bank vegetation grows on an open channel`s side slopes. It has both positive and negative effects, depending on the purpose of the hydraulic conduit. For example, it lowers conveyance capacity by obstructing flow – reducing the flow cross-section area and increasing resistance to flow. On the other hand, it increases bank stability, reduces erosion, provides habitat for aquatic and terrestrial wildlife, and filters pollutants (Nepf *et al.* 1997; Kemp *et al.* 2000; Tang *et al.* 2008).

The impact of ditch bank vegetation on the hydraulic parameters of an open channel (velocity distribution, water surface profile, friction coefficient, etc.) changes in relation to the flow discharge, bank slope, vegetation density, etc.

Several laboratory studies (Afzalimehr & Dey 2009; Hirschowitz & James 2009; Hopkinson & Wynn 2009; Afzalimehr *et al.* 2010; Bledsoe *et al.* 2011; Czarnomski *et al.* 2012; Masouminia 2015; Mohammadzade *et al.* 2016; Liu *et al.* 2017) on the effect of ditch bank vegetation, evaluating and analyzing vegetation effects on velocity distribution, turbulence intensity and kinetic energy, and Reynold's shear stresses. Table 1 is a review summary of the impact of ditch bank vegetation on flow characteristics.

In fact, the impact of ditch bank vegetation depends on many complex, interacting factors, including flow conditions, distance between the ditch bank vegetation and the measurement point, and vegetation spacing.

This study's primary aim was to investigate the effects of rigid ditch bank vegetation on water's surface profile and velocity under subcritical flow, at different discharge rates and vegetation densities in a trapezoidal open channel.

2. EXPERIMENTAL PROGRAM

Experiments were conducted in a 0.6 m wide, 0.42 m deep, 16 m long, horizontal bed, recirculating trapezoidal flume, at the Channel Maintenance Research Institute's hydraulics laboratory. The water level was controlled with a tail-gate at the end of the flume. For all tests, with and without vegetation, a fixed set of 4 discharge rates each with 3 water depths was used.

Simulation of rigid vegetation is common – e.g., in Stone & Shen 2002; James *et al.* 2004; Meftah *et al.* 2006; Kothyari *et al.* 2009; Cheng & Nguyen 2011; Panigrahi 2015; Ahmed & Hady 2017; Chakraborty & Sarkar 2018; Wang *et al.* 2018; and Tong *et al.* 2019. (See Table 2).

In recent research, the rigid vegetation stems have been represented by 3 mm diameter steel rods set in a staggered grid pattern with 25, 50, and 75 mm center spacings, both longitudinally and transversely, and secured above a drilled-hole steel panel. Three vegetation densities – 1,600, 400, and 178 stems/m^2 – were used, with a fixed reach length of 4.00 m at the flume center. Figure 1 shows the experimental channel with vegetation on its sides and Table 3 summarizes the flow conditions of the experiment.

Water depths were measured every 0.50 m along the canal centerline using an ultrasonic level meter (Sondar) in all runs – Figure 2(a). Three velocity profiles were measured – upstream and downstream of, and within the vegetated reach – using a Vectrino (3-D water velocity sensor Lab Probe) – Figures 2(b) and 3.

Table 1 | Summary literature review on the impact of ditch bank vegetation on flow characteristics

			Vegetation model				
				Stem simulation			
Authors	Research type	Simulated channel type	Type Rigid/ Flexible	Diameter (mm)	Density	Distribution	Main Result
Liu *et al.* (2017)	Experimental	Semi-trapezoidal	Rigid	6	10–308 stems/m^2	Both linear and staggered	Increasing the river bank vegetation density increased the velocity in the main channel more than at the riverbank.
Mohammadzade *et al.* (2016)	Experimental	Rectangular	Flexible	4.2 (rice stems)	290 stems/m	Linear	Ditch bank vegetation increased shear stress near the channel bed where the vertical shear stress profile is sigmoid (S- shaped).
Masouminia (2015)	Numerical (3D modeling in FLUENT/ ANSYS)	Semi-trapezoidal	Rigid	6	20–308 stems/m^2	Both linear and staggered	The flow velocity over the side slope becomes less than that over the main channel, initiating a momentum transfer from higher to lower velocity.
Czarnomski *et al.* (2012)	Experimental	Semi-trapezoidal	Rigid	4.54	202 and 615 stems/m^2	Linear	Leaf simulations were an important influence on near-bank turbulence intensities and Reynolds stresses, whereas the side slope's influence was small relative to that of vegetation density.
Bledsoe *et al.* (2011)	Numerical (3D modeling in FLUENT/ ANSYS)	Trapezoidal	Rigid	Simulated as high and low density		Linear	Ditch bank vegetation concentrates flows in the channel center, causing a reduction in shear stresses near the bank zone and increasing them in the channel center.
Afzalimehr *et al.* (2010)	Experimental	Rectangular	Flexible	Rice stems	400 stems/m	Linear	The maximum Reynolds stress occurs near the bed at the flume centerline but, due to the strong effect of the vegetation, it occurs at $y/h=0.5$ near vegetated banks.
Hopkinson & Wynn (2009)	Experimental	Rectangular	Both rigid and flexible	Various configurations			Downstream velocity decreased near the bank for all vegetation treatments, but the reduction did not cause a reduction in total shear stress for all vegetation types.
Afzalimehr *et al.* (2009)	Experimental	Rectangular	Flexible	Wheat stems	Linear along the channel wall		Reynolds stress distribution is non-linear, where there is vegetation along channel side slopes; and depends on the distance from the wall.
Hirschowitz & James (2009)	Experimental	Rectangular	Rigid	5	200 stems/m	Both linear and staggered	An empirical equation was developed to determine channel discharge, using a composite resistance coefficient, which combined the effects of the channel bed and vegetation interfaces.

Table 2 | Summary review of rigid vegetation simulations

	Flume properties				Vegetation model					
						Stem simulation				
		Length	Width						Spacing (Δx)	
Authors	Type	m	m	Bed condition/material	Submergence	Shaped	Material	Diameter (mm)	/Density*	Distribution
Tong *et al.* (2019)	Rectangular	6	0.4	Covered with PVC sheets	Not submerged	Cylindrical	PVC	8	10 cm	Linear
Wang *et al.* (2018)		12.5	0.3	PVC sheets	Not submerged		PVC	10	Density (1, 2 and 4%)	Staggered
Chakraborty & Sarkar (2018)		10	0.4	Plexiglas's	Submerged		PVC	6	Random Distribution	
Ahmed & Hady (2017)		12	0.4	Sand (d50=0.62)	Submerged		PVC	10	22.72, 11.9, and 9.61 cm	Linear
Panigrahi (2015)		12	0.6	Water-resistant plywood sheet	Both submerged and not submerged		Iron	6.5	10 cm	Both linear and staggered
Cheng & Nguyen (2011)		12	0.3	Steel	Not submerged		Steel	3.2, 6.6 and 8.3	3 and 6 cm	Staggered
Kothyari *et al.* (2009)		16	0.5	Stainless steel	Not submerged		Stainless steel	10	3.2–20.3 cm	Staggered
Meftah *et al.* (2006)		8	0.3	Water-resistant plywood sheet	Submerged		Metallic	3	10 cm	Linear
James *et al.* (2004)		3	0.1	Sand (d50=0.48)	Not submerged		Steel	5	2.5, 5, and 7.5 cm	Staggered
Stone & Shen (2002)		12	0.45	Water-resistant plywood sheet	Both submerged and not submerged		Wood	3.18, 6.35 and 12.7	3.8, 4.6 and 7.6 cm	Staggered
This study	Trapezoidal	16	0.6	concrete	Not submerged	Cylindrical	Steel	3	2.5, 5, and 7.5 cm	Staggered

Density*: the ratio of the bottom areas of all stems to that of the flume area for the vegetated section.

Figure 1 | Artificial canal, with rigid vegetation on the channel side slopes.

Table 3 | Experimental conditions

Vegetation properties							
Vegetation density	**Arrangement**	**Spacing cm**	**Stems/m^2**	**Flow condition**	**Discharge (l/s)**	**Tailwater depth****	**No of runs**
Unvegetated	n/a	n/a	n/a	Subcritical flow	40, 35, 30, 25	Three different depths for each discharge	12
High (λ>0.0113)	Staggered	2.5	1,600		40, 35, 30, 25		12
Medium (λ>0.0028)		5.0	400		40, 35, 30, 25		12
Low (λ>0.0013)		7.5	178		40, 35, 30, 25		12
Runs (total)							48

**The tailwater depths are related to three Froude number ranges for the unvegetated case (Fr_o); 1. Fr_o=0.11–0.15; 2. Fr_o=0.15–0.20 and 3. Fr_o=0.21–0.30.

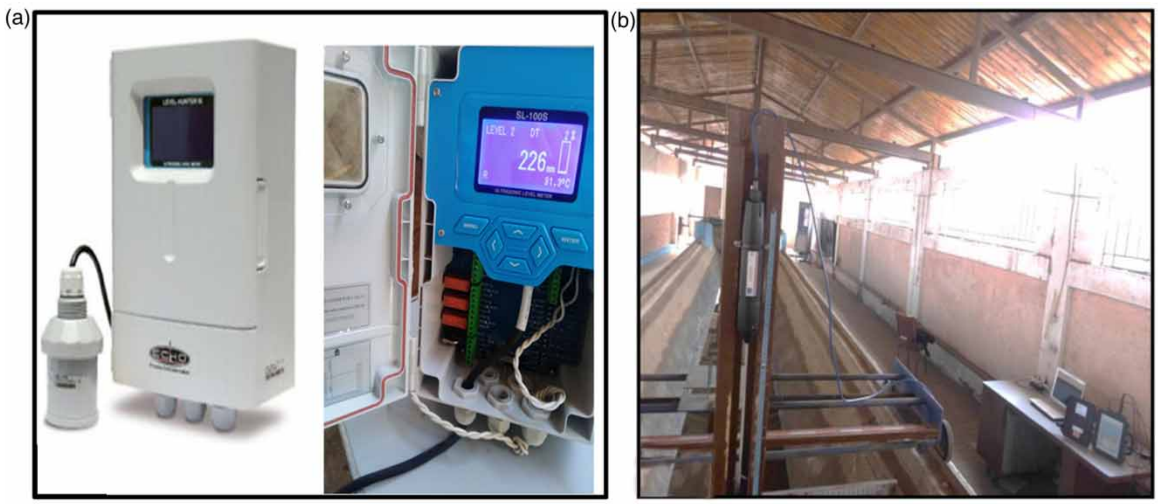


Figure 2 | Experimental tools. (a) ultrasonic level meter (Sondar) and (b) Vectrino 3D water velocity sensor.

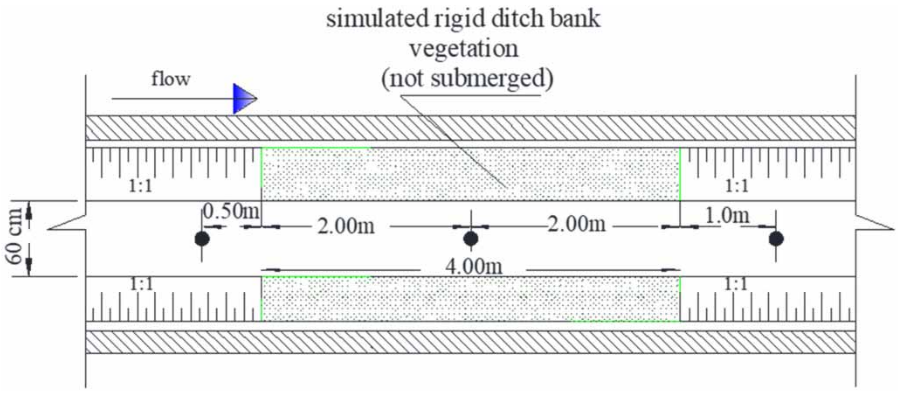


Figure 3 | Velocity measuring points upstream, within, and downstream of the vegetated reach.

3. DIMENSIONAL ANALYSIS

Buckingham's Pi-theorem was used for dimensional analysis to determine the relationship between vegetation density, and the changes in water depth and velocity within the vegetated reach. The relationships obtained can be written in the form of Equation (1). Figure 4 is a definition sketch of the ditch bank vegetation channel and shows the measurement locations.

$$\left(\frac{\mathrm{Y_{in}}}{\mathrm{Y_o}}, \left(\frac{\mathrm{V_{in}}}{\mathrm{u}}\right)_{\mathrm{max}}\right) = f(\lambda, Fr_o) \quad (1)$$

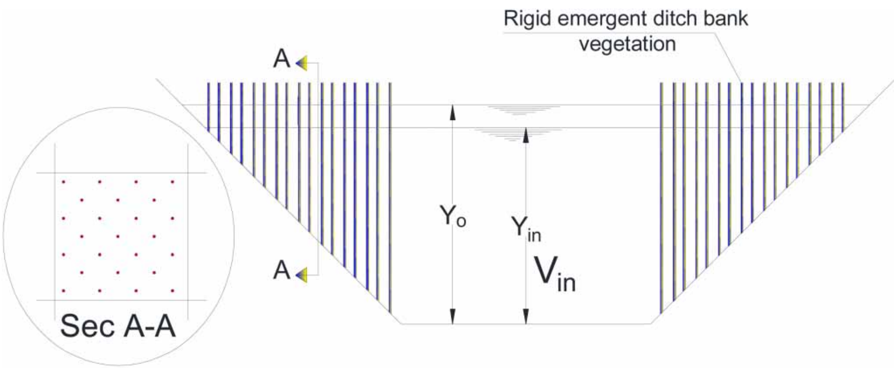


Figure 4 | Cross-section of the vegetated reach.

where, Y_{in} is the average water depth along the centerline of the vegetated reach (m), Y_o the water depth in the unvegetated case (m), V_{in} the flow velocity in the middle of the vegetated reach (m/s), the corresponding velocity in the unvegetated case (m/s), the vegetation density (the cross-sectional area of the cylinders (stems) per unit bank area, $\lambda = \Pi\ N^0\ d^2/4$, where N^0 is the number of stems per unit side area and (d) the stem diameter (m), and Fr_o is the Froude number in the unvegetated case.

$$\mathrm{Fr_o} = \bar{\mathrm{u}}/\sqrt{gY_O} \quad (2)$$

where ū is the average velocity in the unvegetated case (m/s) and is the gravitational acceleration (m/s^2).

4. RESULTS AND ANALYSIS

4.1. Effect of ditch bank vegetation on flow parameters

4.1.1. Water surface profile through the vegetated reach

The water surface profile along the flume centerline was surveyed with an ultrasonic level meter, to understand the influence of vegetation density on it. The water profiles arising at different vegetation densities are shown in Figure 5.

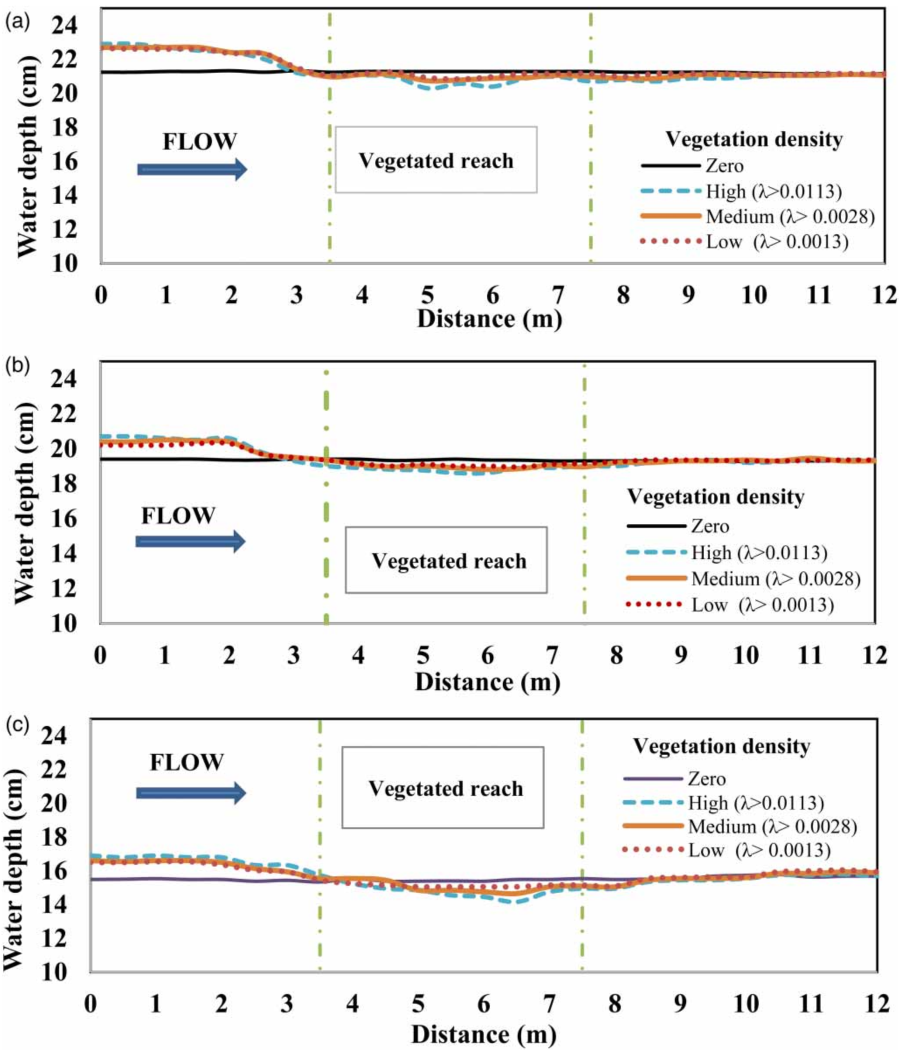


Figure 5 | Canal water surface profile at Q=40 l/s with different vegetation densities, for (a) Fr_o=0.15, (b) Fr_o=0.20, and (c) Fr_o=0.30.

As can be seen in Figure 5, the water depth increased upstream of the vegetated reach, but fell within the reach, compared to the unvegetated case. The relationship between water depth reduction in the vegetated reach, at different vegetation densities, and Fr_o (unvegetated), is illustrated in Figure 6

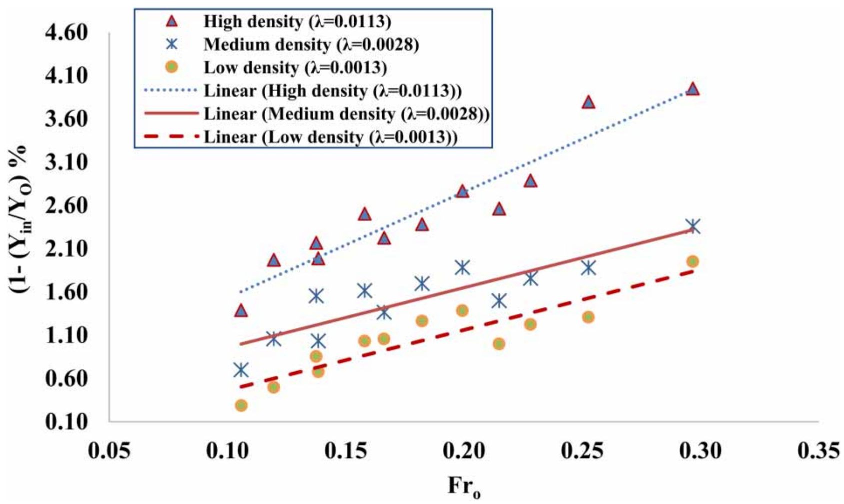


Figure 6 | Relationship between water depth reduction (Y_{in}/Y_o) within the vegetated reach and Fr_o in the unvegetated case.

Figure 6 shows a positive relationship between Fr_o and the proportional water depth reduction (%). The proportional reduction within the vegetated reach increased with both increasing Fr_o and vegetation density.

Maintenance programs should be applied to manage ditch bank vegetation in open channels, because water level changes upstream of and within the vegetated reach which affects water distribution on branches as well as the calibration of opening gates. Drainage collectors will also be affected.

4.1.2. Impact of ditch bank vegetation on the velocity distribution

The water velocity sensor was mounted on a carriage to measure flow velocity in different vertical sections along the flume centerline. This was done upstream, within, and downstream of the vegetated reach. Figures 7–9 show the velocity profiles for different vegetation densities as ratios of the velocity in the unvegetated cases. In the figures, the term h/Y is the ratio between the vertical measuring distance (h) and the total water depth (Y).

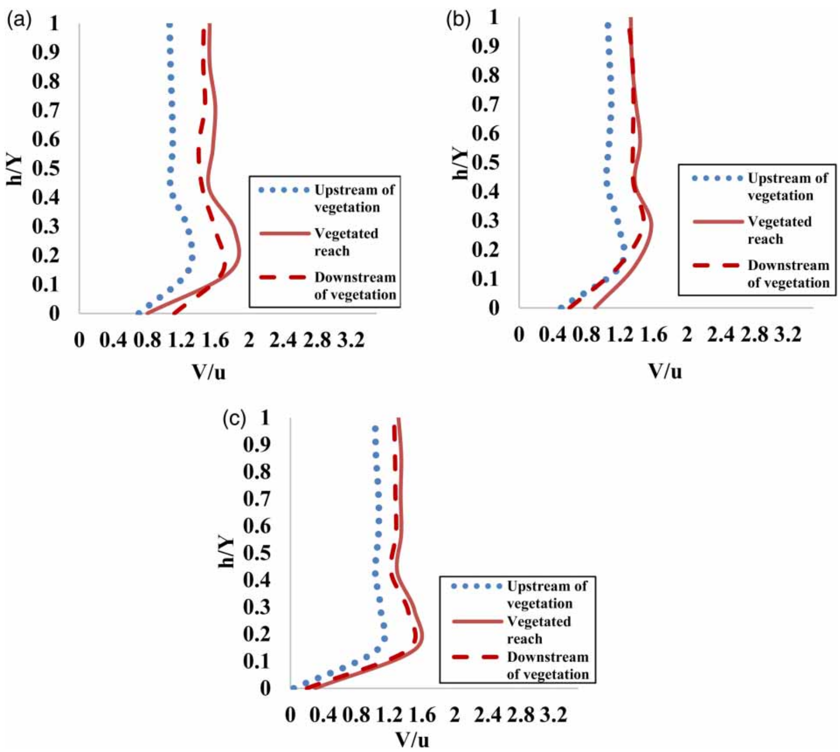


Figure 7 | Velocity profiles for different vegetation densities (λ) at Q=40 l/s and Fr_o=0.15, for (a) λ=0.0113, (b) λ=0.0028, and (c) For low λ=0.0013.

The velocity profile as a ratio of the unvegetated case (V/u) is sigmoid, i.e. the maximum velocity (V/u_{max}) occurs in the lower half of the water column. The reason for increasing velocity near the channel bed may be the secondary current that occurs due to the presence of the side vegetation. This result accords with the work of (Afzalimehr & Dey 2009; Afzalimehr *et al.* 2010; Masouminia 2015; Mohammadzade *et al.* 2016; Liu *et al.* 2017), where it is concluded that the level of maximum velocity in the presence of vegetation on the channel walls is below the water surface and the maximum shear stress occurs near the channel bed.

Channel-side vegetation increases flow velocity near the bed – i.e., shear stress near the bed increases – which, in turn, increases the possibility of bed erosion on the vegetated channel's centerline. It is also noted that V/u increases with increasing vegetation density and correlates directly with the change in Fr_o in the unvegetated case at the same discharge – i.e., V/u is influenced by channel geometry. The maximum velocity occurred within the vegetated reach and is close to that measured just downstream of the vegetation. Figure 10 shows the relationship between V/u_{max} within the vegetated reach and Fr_o at different vegetation densities.

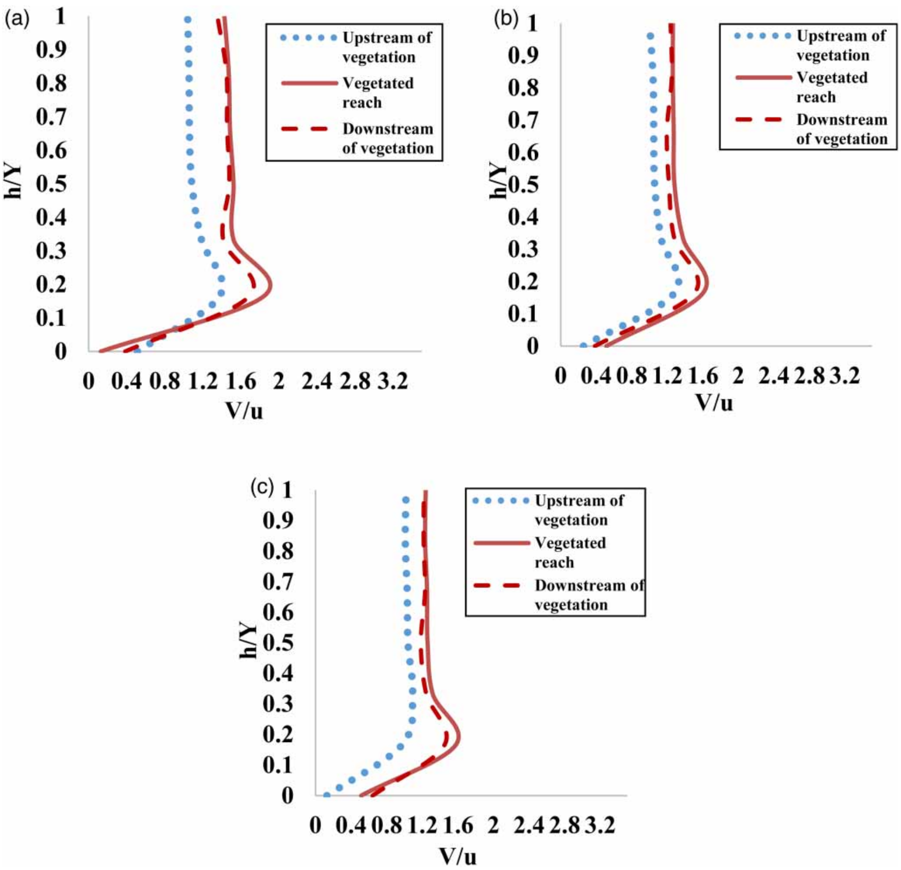


Figure 8 | Velocity profiles for different vegetation densities (λ) at Q=40 l/s and Fr_o=0.20, for (a) λ=0.0113, (b) λ=0.0028, and (c) λ=0.0013.

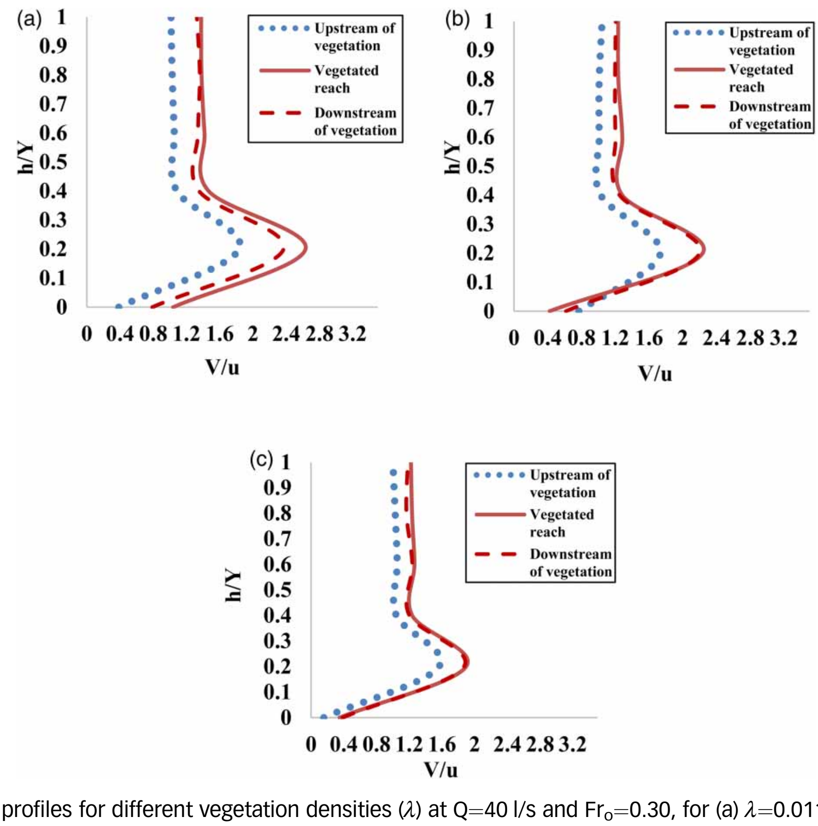


Figure 9 | Velocity profiles for different vegetation densities (λ) at Q=40 l/s and Fr_o=0.30, for (a) λ=0.0113, (b) λ=0.0028, and (c) λ=0.0013.

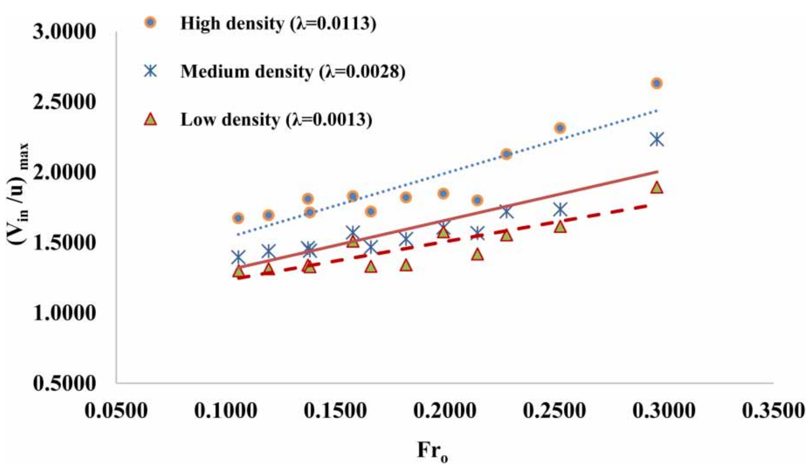


Figure 10 | Relationship between V_{in}/u_{max} and Fr_o in the unvegetated case.

4.2. Empirical relationships

DataFit 9.0 statistical software packages were used for both statistical analysis and deriving empirical relationships (Oakdale Engineering 2008). A multiple regression analysis was performed at 95% confidence level. R^2 was used as a measure of goodness of fit, where the predicted value indicates how well the model predicts responses for new observations.

4.2.1. Relationship between λ and Y_{in}/Y_o within the vegetated reach

An empirical equation was developed to assess the impact of ditch bank vegetation density on the decrease in water depth within the vegetated reach – Equation (3).

$$\frac{Y_{in}}{Y_o} = 0.92\,(\lambda)^{-0.007}\,(Fr_o)^{-0.015} \quad R^2 = 0.89 \tag{3}$$

All contributing factors were shown to be significant in prediction, i.e., all factors had p-values <0.0001. Tables 4 and 5 show the regression analysis results from Equation (3) and the significance of each variable. Figure 11 is a plot of the predicted and measured water depth decreases in the vegetated reach.

Table 4 | Regression analysis results – Equation (3)

Variance Analysis

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob (F)
Regression	2	0.002	0.001	129.269	0.000
Error	33	0.000	0.000		
Total	35	0.002			

Table 5 | Coefficient and significance of variables in Equation (3)

Variable	Value	Lower Limit	Upper Limit	Standard Error	t-ratio	Prob(t)
a	0.92	0.91	0.93	0.00	239.57	0.00
b	−0.007	−0.008	−0.006	0.00	−12.95	0.00
c	−0.015	−0.019	−0.012	0.00	−9.49	0.00

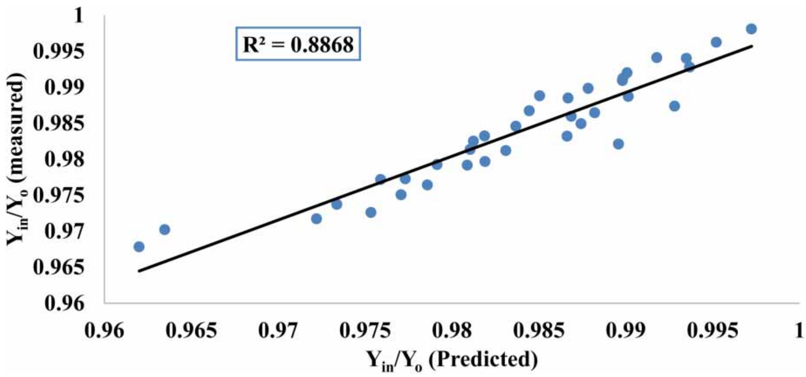


Figure 11 | Comparison of measured and predicted $\frac{Y_{in}}{Y_o}$.

4.2.2. Relationship between λ and the average velocity within the vegetated reach $(V_{in}/u)_{max}$

An empirical equation – Equation (4) – was also developed to assess the impact of ditch bank vegetation density on velocity within the vegetated reach.

$$\left(\frac{V_{in}}{u}\right)_{max} = 6.79(\lambda)^{0.128}\,(Fr_o)^{0.403} \quad R^2 = 0.85 \tag{4}$$

All contributing factors were shown to be significant in prediction, i.e., all had p-values <0.0001. Tables 6 and 7 show the results of regression analysis of Equation (4) and the significance of each variable. Figure 12 is a plot of the predicted and measured velocity ratios $((V_{in}/u)_{max})$ within the vegetated reach.

Table 6 | Regression analysis results – Equation (4)

Variance Analysis

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob(F)
Regression	2	0.433	0.217	76.798	0.000
Error	33	0.093	0.003		
Total	35	0.526			

Table 7 | Coefficient and significance of variables in Equation (4)

Variable	Value	Lower Limit	Upper Limit	Standard Error	t-ratio	Prob(t)
a	1.74	1.56	1.92	0.09	19.85	0.00
b	0.079	0.065	0.093	0.01	11.46	0.00
c	0.048	0.028	0.068	0.01	4.81	0.00

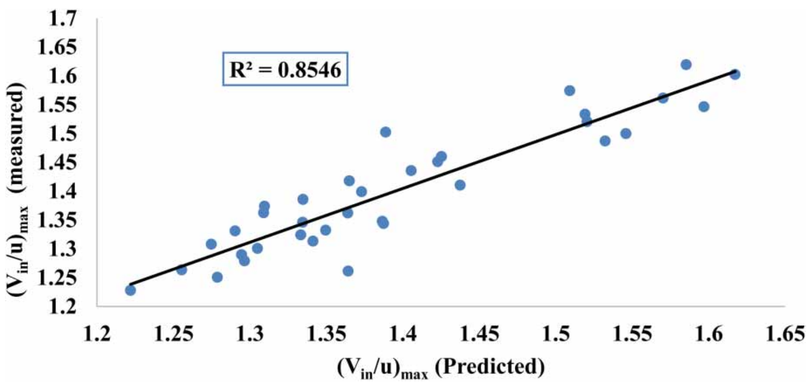


Figure 12 | Comparison between measured and predicted $(V_{in}/u)_{max}$

5. CONCLUSIONS

The effect of rigid ditch bank vegetation on water surface profile and velocity distribution under sub-critical flow conditions at different discharge rates and vegetation densities in a trapezoidal open channel was studied. It was noted that:

1. Increasing the ditch bank vegetation density increases the water depth upstream of the vegetated reach significantly and reduces it within the vegetated reach.
2. The decrease in water depth within the vegetated reach increased with increasing Fr_o.
3. The velocity profile as a ratio of that of the unvegetated case (V/u) is sigmoid (S-shaped).
4. V/u increased with increasing vegetation density and is also correlated directly with the change in Fr_o.
5. V/u is influenced by channel geometry.
6. The maximum velocity occurred within the vegetated reach and is close to that measured just downstream of the vegetated reach.
7. V/u_{max} occurs in the lower half of the water column, which increases shear stress near the bed and increases the possibility of bed erosion on the vegetation channel's centerline.
8. Multiple regression analysis and the development of empirical equations were used to assess the impact of vegetation density on the reduction in water depth within the vegetated reach and its effect on flow velocity there.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICTS OF INTEREST

The authors declare there is no conflict.

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