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Effect of Water Hyacinth on Open-Channel Water Flow Behavior: Laboratory Scale

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ABSTRACT

Water hyacinth (*Eichhornia crassipes*) is one of the fastest growing plants. Due to its ability to adapt and reproduce, it causes various problems in waterways. The effect of water hyacinth was investigated on flow behavior in an open channel in a laboratory flume. Five different root depths of water hyacinth from natural streams were modeled using a plant floating plate. Four different water hyacinth densities were used. Controls without water hyacinth were also established. The vertical velocity profiles of the cases with and without water hyacinth were compared and the results showed that without water hyacinth, the velocity profile was similar to the theoretical logarithmic distribution in an open channel. In the cases with water hyacinth, the vertical velocity profiles were similar to the theoretical velocity distribution in a closed conduit, in which the velocity in the root zone was zero since water hyacinth floating on the water surface behaved like a solid wall. The experimental data showed that the plant caused flow resistance which tended to slow down the flow. Furthermore, the denser and longer root depth of water hyacinth caused greater flow resistance, as the flow-retarded region extended deeper, occupying about 65.0% of flow depth measured from the water surface. In addition, an empirical formula for flow in an open channel with consideration of water hyacinth effects was developed and a flow velocity empirical formula was obtained which was in good agreement with the observed data used in the verification process.

Keywords: manning coefficient, plant density, the water hyacinth effect coefficient, velocity profile, water hyacinth

INTRODUCTION

Water hyacinth (*Eichhornia crassipes*) is one of the fastest growing plants which commonly spread within streams and water areas and is a native plant of South America brought for cultivation in various places in North America, Australia, Africa and Europe for use as an ornamental plant and flower (Sullivan *et al.*, 2012). In 1901, it was brought from Indonesia to Thailand because of it beautiful flowers (Prapaiwong and Ruanteetep, 1995), as shown in Figure 1. Subsequently, it has spread extensively in all rivers and water bodies around the country and its ability to adapt and reproduce has causes various problems in waterways with regard to both hydraulic and water quality issues (Saknimit, 1976).

Several researchers have investigated and developed mathematical models to predict the effects of the aquatic plant on the water flow. Shimizu *et al.* (1994) studied the effect of plants

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as an impermeable fence on flow resistance and horizontal velocity pattern changes in the Tedori River. Boman *et al.*(2002) investigated the resistance of grass in streams. Ghisalberti and Nepf (2004) investigated the effect of circular wooden submerged cylinders on the flow velocity. Wilson (2007) examined the effects of grass blades on the flow resistance in small and large channels and Liu *et al.* (2010), investigated the flow effect due to sparse grass stem arrays. However, floating plants such as water hyacinth have not been studied widely, perhaps because it is not considered to be a serious problem other than in the tropics. It is suspected that the existences of water hyacinth substantially alters the bulk and time-averaged flow characteristics, which then might influence changes in the river morphology.

The current study investigated the effect of water hyacinth on the water flow, especially during a flood period, since the plant introduces roughness elements on the water surface. A laboratory experiment was arranged as an open channel flume. The water hyacinth root depth (h′) and density (λ) were set up as the control parameters and the nature of the effects was clarified. The overall objectives of the study were: 1) to investigate the effects of water hyacinth on the vertical flow velocity distribution and the flow velocity in a horizontal direction; 2) to investigate the effects of water hyacinth root depth (h′) and density (λ) on the average flow velocity; and 3) to develop an empirical formula of the water flow in an open channel taking into consideration water hyacinth effects.

MATERIALS AND METHODS

The experiments were carried out in a laboratory of the Department of Water Resources Engineering, Kasetsart University, Bangkok, Thailand. The materials used were: 1) a rectangular-section flume made from stainless steel and acrylic with dimension of 0.3 m × 0.4 m × 15 m set up with a 1 in 1,000 slope, as shown in Figure 2; 2) water hyacinth plants with a root depth of approximately 2.5, 5.0, 10.0, 20.0 and 30.0 cm harvested from natural streams and attached to a plant floating plate of dimension 0.3 m × 6.0 m. The plant floating plate with affixed water hyacinth was held in plastic foam sheets suspended 2 cm above the water surface along the channel since the study investigated the roughness elements on the water surface directly, as shown in Figures 3 and 4; 3) to study the effect of the water hyacinth density on the flow, four different levels of water hyacinth density (λ) were used with the number of water hyacinth plants on the floating plate being: λ=0.25 (approximately 32 stems.m^{-2}), λ=0.5 (approximately 64 stems.m^{-2}), λ=0.75 (approximately 96 stems.m^{-2}) and λ=1.0

Figure 1 Sample of water hyacinth (*Eichhornia crassipes*).

Figure 2 Water flume used in the experiment.

(approximately 128 stems.m^{-2}); and 4) flume accessories consisting of a flow meter, depth gauge and mini current meter.

A flow diagram of the study is shown in Figure 5.

Figure 3 Water hyacinth in natural streams was harvested and used in the experiment.

Figure 4 Plant floating plate used in the experimental flume.

Figure 5 Workflow chart of the study.

Experiments were conducted with and without (the control) water hyacinth. In each experiment, the flow conditions were identical using a steady, uniform flow with average velocities of approximately 0.5, 0.7 and 0.9 $m.s^{-1}$. During the experiment, the flow was controlled upstream and was measured at depths at sections 1, 2, 3 and 4 that were 2 m apart along the flume, as indicated in Figure 6. Multiple measurements were averaged. In addition, the vertical velocities were measured at different depths (10, 20, 30, 40, 50, 60, 70 and 80% of the depth at the designated section), as shown in Figures 7 and 8.

The harvested water hyacinth was set up on the water surface using four different water hyacinth densities designated as λ in further calculations (Urantinon and Pilailar, 2014). In each water hyacinth density experiment, the specific plant root depth was set up using a plant floating plate on the water surface. The flow at the three different velocities was controlled and the vertical velocities were measured both with and without water hyacinth.

In addition, with water hyacinth in the various cases with different plant densities and root depths (Case 2), the average depth record

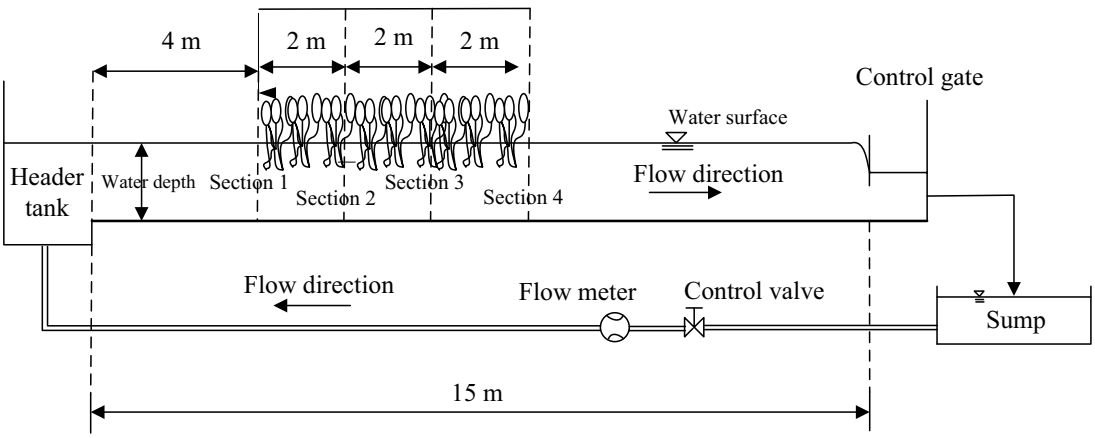


Figure 6 Water depth measurement sections, along the experimental flume.

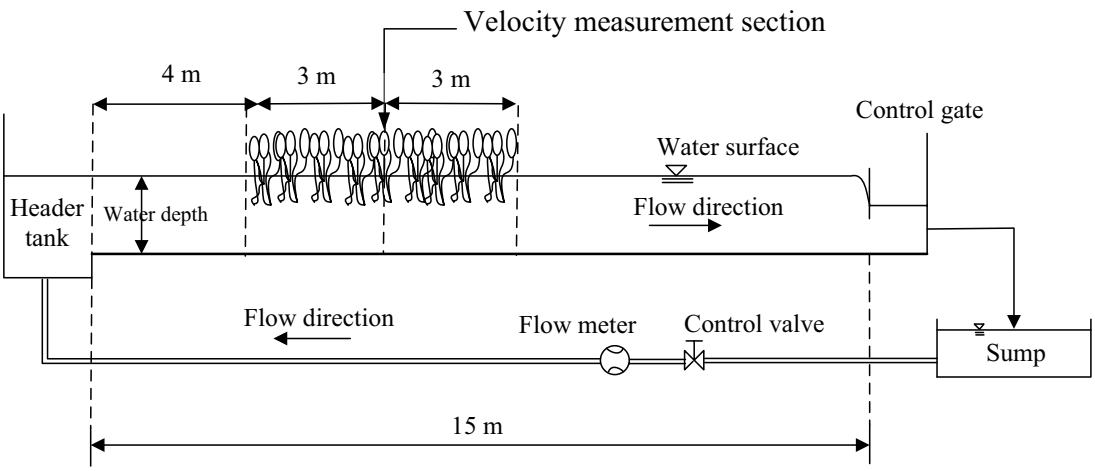


Figure 7 Velocity measurement section of the flume.

were recorded as Set A and the vertical velocities were recorded as Set B. Finally, the flow velocities profile (Case 1) was compared with Set B to determine the flow behavior effect with water hyacinth in the open channel. Set A was used for the development of the empirical formula of flow in an open channel with water hyacinth and Set B was used in the verification process.

RESULTS AND DISCUSSION

Vertical velocity profile

The vertical velocity profiles (V = 0.5, 0.7 and 0.9 $m.s^{-1}$) without water hyacinth ($\lambda = 0.0$) and with water hyacinth ($\lambda = 0.5, 1.0$) are shown in Figures 9, 10 and 11. Without water hyacinth, there was a higher vertical velocity profile (Figures 9a, 10a and 11a) at the water surface and zero velocity near the bed since the roughness element on the bed was greater than at the water surface. Thus, the velocity profile was similar to the theoretical logarithmic distribution in an open channel (Figure 12a).

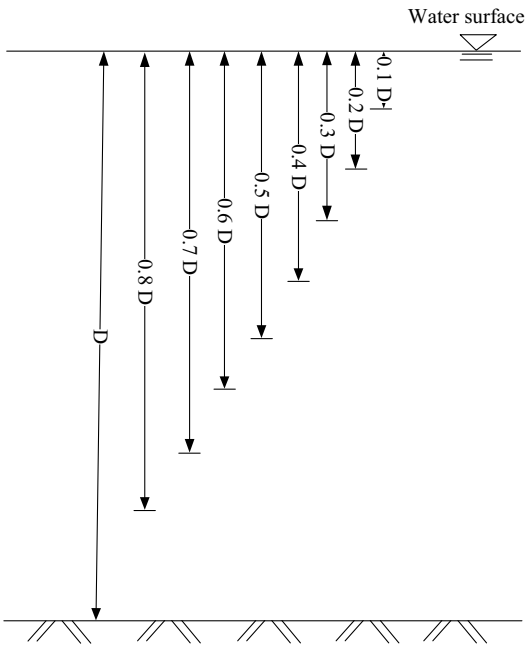


Figure 8 Vertical velocity measurement points at designated sections in the flume.

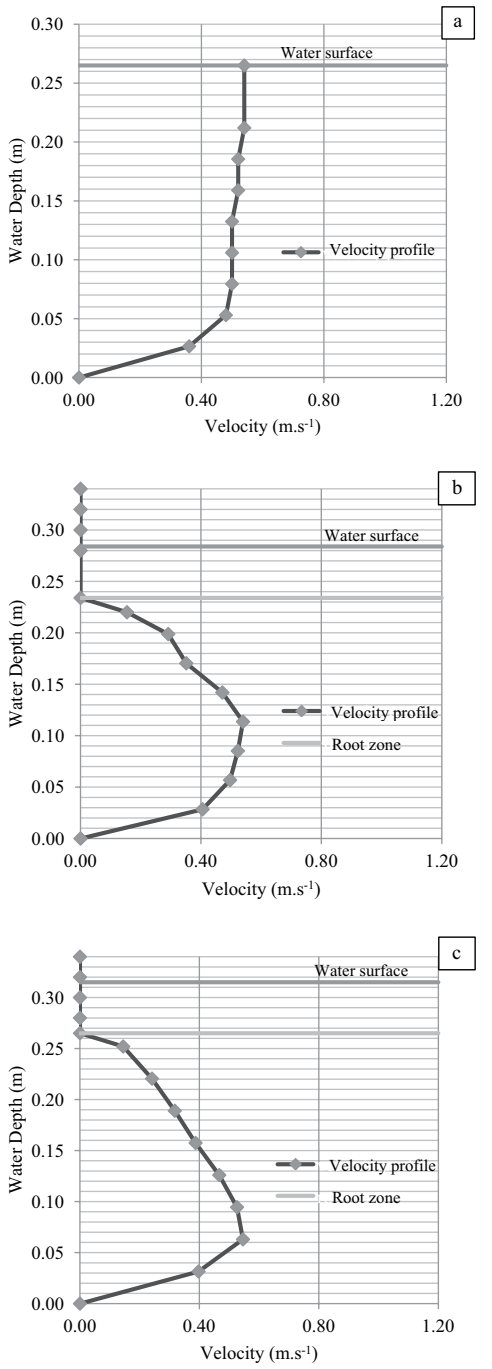
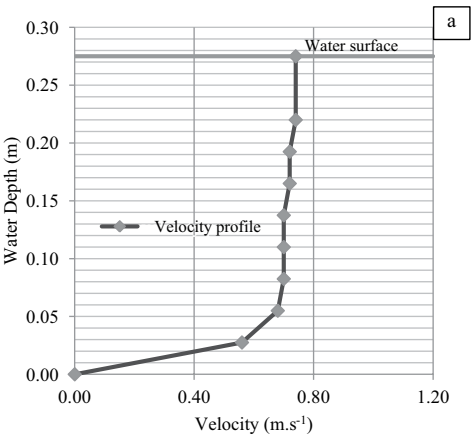
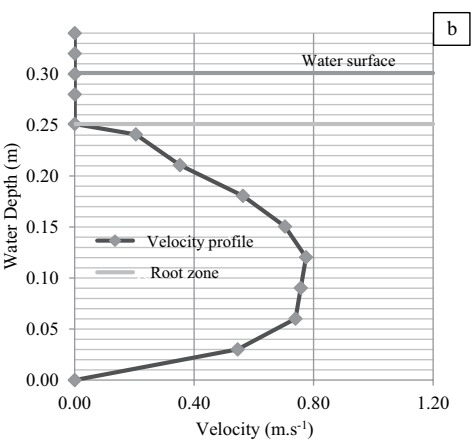


Figure 9 Velocity (V = 0.5 $m.s^{-1}$,) profiles in vertical direction at the selected cross-section: (a) Without water hyacinth (plant density (λ) = 0.0); (b) With water hyacinth ($\lambda = 0.5$, root depth (h') = 0.05m); (c) With water hyacinth (λ = 1.0, h' = 0.05m).





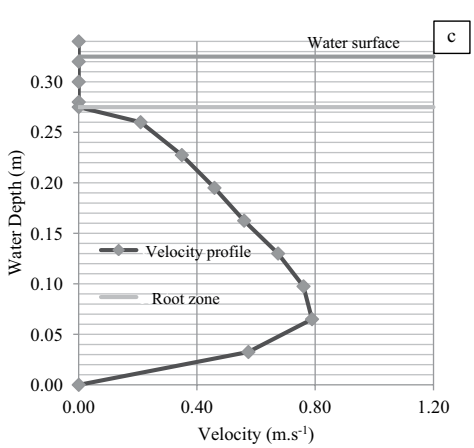
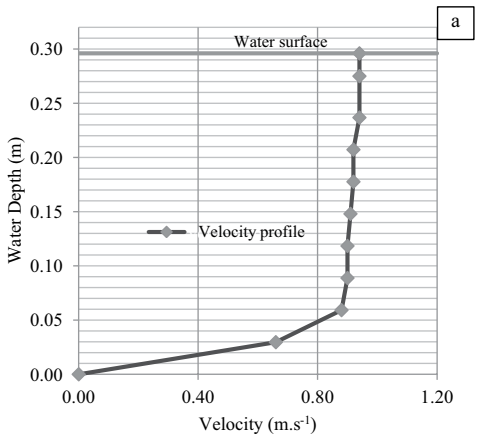
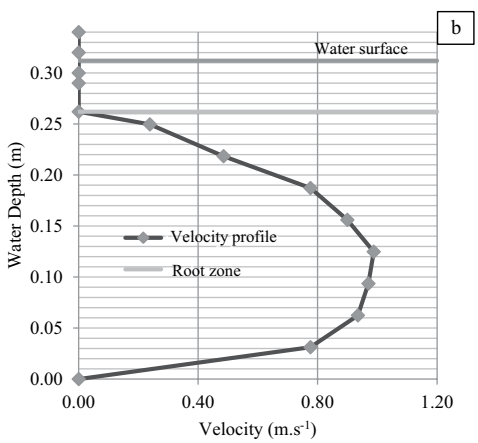


Figure 10 Velocity (V = 0.7 m.s^{-1}) profiles in vertical direction at the selected cross-section: (a) Without water hyacinth (plant density (λ) = 0.0); (b) With water hyacinth (λ = 0.5, root depth (h') = 0.05m); (c) With water hyacinth (λ = 1.0, h' = 0.05m).





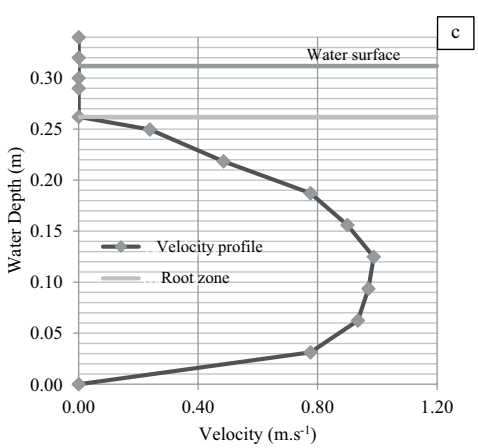


Figure 11 Velocity (V = 0.9 m.s^{-1}) profiles in vertical direction at the selected cross-section: (a) Without water hyacinth (λ = 0.0); (b) With water hyacinth (λ = 0.5, root depth (h') = 0.05m); (c) With water hyacinth (λ = 1.0, h' = 0.05m).

The velocity profiles (V = 0.7 m.s^{-1}) with water hyacinth (λ = 0.5 and 1.0) were similar to the theoretical velocity distribution in a closed conduit (Figure 12b) due to the flow resistance at the water surface. The resistance at the water surface was caused by the plant density, which tendeds to slow down the flow velocity. The slope of the velocity profile was greater with a higher plant density since the increasing number of plants increased the roughness element on the water surface. The zero velocity below the plant root zone resulted from the plant density. The plant density was the main reason for the resistance in the flow, since the plant floating plate was suspended 2 cm above water surface along the channel. It was confirmed by the experimental results in cases V = 0.5 and 0.9 m.s^{-1}, respectively, since the surface resistance was greater than the bed resistance, the resulting vertical velocity distributions were not symmetrical, as seen in Figures 9b, 10b and 11b and Figures 9c, 10c and 11c, respectively.

Finally, the velocity profiles showed the retardation of flow below the plant root zone, depending on the plant density (λ). For V = 0.7 m.s^{-1}, greater retardation was observed for λ = 1 than for λ = 0.5, while for λ = 1.0, the flow retarded region extended deeper, occupying about 65% of the flow depth measured from the water surface, whereas for λ = 0.5, the retarded zone occupied only 40% of the depth from the water surface. These results indicated that the denser the water hyacinth, the greater the flow friction and was confirmed by the results of the velocity profiles V = 0.5 and 0.9 m.s^{-1} which produced an extended retarded region, occupying about 50 and 70% of the flow depth, respectively, whereas for λ = 0.5, the retarded zone occupied only 30 and 45%, respectively.

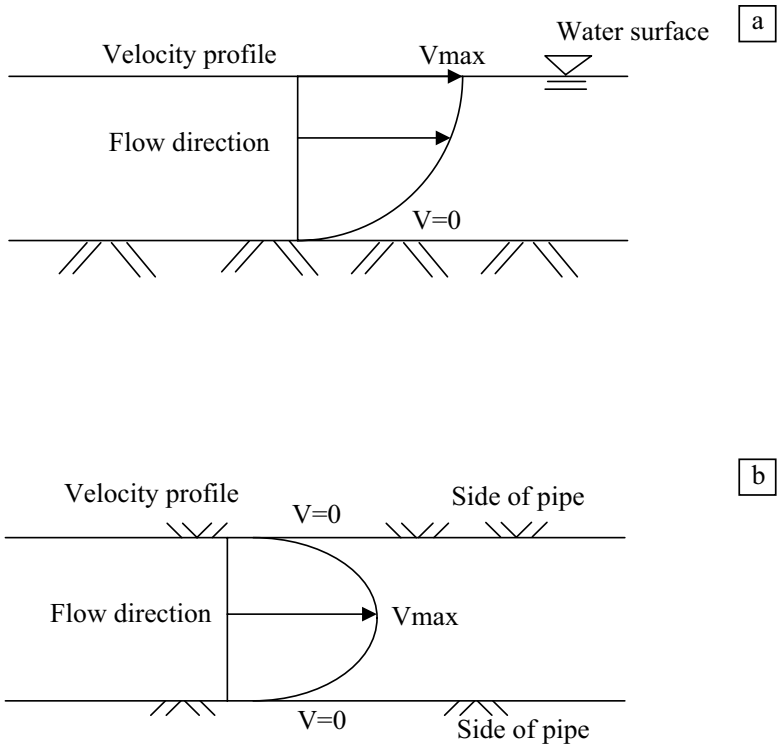


Figure 12 Theory of velocity profiles in vertical direction: (a) Theoretical velocity distribution in vertical direction in open channel; (b) Theoretical velocity distribution in vertical direction in closed conduit. V = Velocity, Vmax = Maximum velocity.)

Effect of water hyacinth density and root depth variations on average flow velocity and flow resistance

To compare the effect of the water hyacinth density and root depth on the theoretical flow velocity, the measured depths were converted for use with the continuity equation, as shown in Equation 1:

$$V = Q / A \quad (1)$$

where, V is the flow velocity measured in meters per second, Q is the flow discharge measured in cubic meters per second and A is the area measured in square meters.

The average Manning coefficients, that represent the degree of friction resistance, can be determined using the Manning equation (Chow, 1959), shown in Equation 2:

$$n = (R^{2/3} S^{1/2})/V \quad (2)$$

where R is the hydraulic radius measured in meters, S is the channel slope and V is the flow velocity measured in meters per second.

The comparisons of the average velocity and average Manning coefficient for the water hyacinth root depth of 5 cm are shown in Table 1 which shows that the denser the water hyacinth (λ = 0.00, 0.25, 0.50, 0.75 and 1.00), the greater the friction coefficient; (Manning coefficients of 0.010, 0.011, 0.0114, 0.0118 and 0.0125, respectively). This indicates the retardation of flow due to water hyacinth in the waterway, with the degree of flow resistance dependent on the density of the water hyacinth.

The effect of root depth on the flow resistance using the case where the surface water was fully covered by water hyacinth (λ = 1.00) is shown in Table 2. Without water hyacinth, the averaged Manning coefficient was 0.010, which was smaller than for the cases with water hyacinth. In addition, the longer the root depth, the greater the Manning coefficient, as the maximum Manning coefficient was 0.0149 for a hyacinth root depth of 30.0 cm which retarded the flow velocity up to 21.72%.

Development of empirical formula of flow in open channel with water hyacinth effects

To develop the empirical formula of flow in an open channel with water hyacinth density and root depth variations, the water hyacinth effect coefficient (C_{hy}) was assumed to be the ratio of the velocity without water hyacinth ($V_{w/o}$) and the velocity with water hyacinth (V_w) as shown in Equation 3:

$$C_{hy} = V_{w/o} / V_w \quad (3)$$

and was considered to be a function of the plant density (λ) and plant root depth (h′) and water depth (d) as expressed in Equation 4:

$$C_{hy} = f^n (h' / d , \lambda) \quad (4)$$

Table 1 Comparison of average velocity and Manning coefficient with and without water hyacinth at different water hyacinth densities (λ) for a water hyacinth root depth of 0.05 m.

λ	0.00	0.25	0.50	0.75	1.00
Average velocity ($m.s^{-1}$)	0.700	0.680	0.613	0.583	0.548
Manning coefficient ($s.m^{-1/3}$)	0.010	0.0110	0.0114	0.0118	0.0125

Table 2 Average velocity for five cases of root depth for full water hyacinth coverage (λ = 1.00).

Root depth (m)	0.000	0.025	0.050	0.100	0.200	0.300
Average velocity ($m.s^{-1}$)	0.700	0.574	0.562	0.538	0.499	0.466
Manning coefficient ($s.m^{-1/3}$)	0.0100	0.0107	0.0125	0.0132	0.0144	0.0149

where depths are all measured in meters

By using the PI theorem (White, 1994), the C_{hy} function shown in Equation 5 can be obtained:

$$C_{hy} = 1.0 + (h' / d)^{0.397} + \lambda^{0.184} \quad (5)$$

The accuracy of Equation 5 was confirmed by the comparison of C_{hy} from the calculation (C_{hy_cal}) and C_{hy} from the experiments (C_{hy_exp}), as shown in Figure 13. As the relationship between $C_{hy\_cal} / C_{hy\_exp} = 1$, Equation 5 provides good reliability and thus, it was appropriate to be applied further.

By, substitution of C_{hy} in Equation 3, the flow velocity with the relevant water hyacinth effect can be obtained, as shown in Equation 6:

$$V_w = \frac{V_{w/o}}{1.0 + (\frac{h'}{d})^{0.397} + (\lambda)^{0.184}} \quad (6)$$

In addition, the average Manning coefficient, n_{hy}, can also been calculated, as shown in Equation 7:

$$n_{hy} = \frac{(1.0 + (\frac{h'}{d})^{0.397} + (\lambda)^{0.184}) R^{2/3} S^{1/2}}{V_{w/o}} \quad (7)$$

where R is the hydraulic radius measured in meters and R = A / P; A is the cross-section area measured in square meters; P is the wetted perimeter and P = 2(b+d), and b is the channel width and d is the water depth, all measured in meters and S is the channel slope.

Empirical formula verification

To verify the empirical formula of the flow velocity with water hyacinth effects, the calculated flow velocities from Equation 6 were compared with the flow velocity measured in the experiment. The comparison is shown in Figure 14.

The calculated flow velocities using the empirical formula showed good agreement with the measured velocity, with a coefficient of determination of 0.946. Therefore, the empirical formula of the flow velocity including the water hyacinth effects obtained in this study was clearly verified.

CONCLUSION

The effect of water hyacinth on water flow was investigated in the laboratory, under conditions of a steady, uniform flow with average velocities of approximately 0.5, 0.7 and 0.9 $m.s^{-1}$.

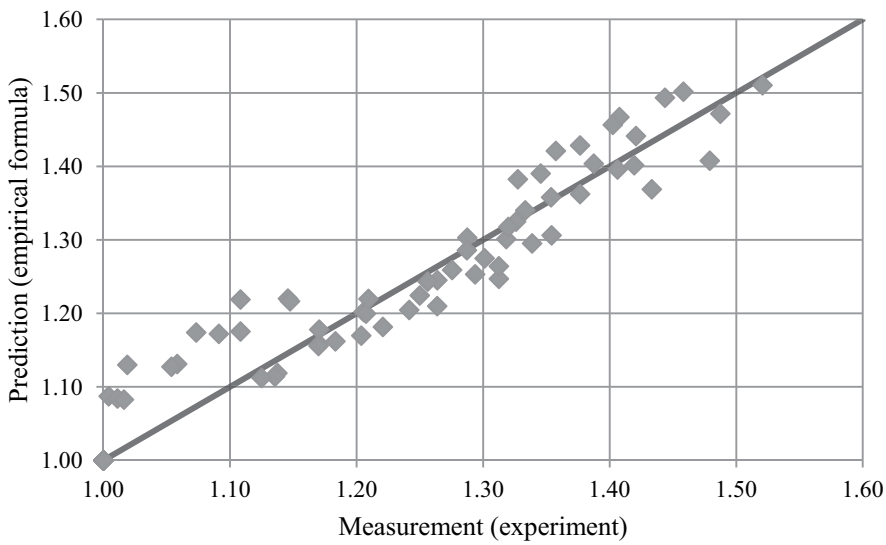


Figure 13 Comparison between predictions from empirical formula and measurements from experiment.

It was found that water hyacinth floating on the water surface behaved like a solid wall since the vertical velocity profiles with differing amounts of water hyacinth were similar to the theoretical velocity distribution in a closed conduit, with a zero velocity in the root zone. This was due to the flow resistance at the water surface which was caused by the plant density; increased density tended to slow down the flow velocity. The slope of the velocity profile was greater with a higher plant density since the greater number of plants increased the roughness element on the water surface. The zero velocity below the plant root zone resulted from the plant density. The plant density was the main reason for the flow resistance, since the plant floating plate was suspended 2 cm above water surface along the channel. This was confirmed by the experimental results for cases of V = 0.5 and 0.9 $m.s^{-1}$, respectively. The experimental data showed that the plant caused flow resistance which tended to slow down the flow. The data also indicated that a denser and longer root depth of water hyacinth caused greater flow resistance, as the flow-retarded region extended deeper, occupying about 65% of the flow depth measured from the water surface where that surface water was fully covered with water hyacinth. This was confirmed by the results of the velocity profiles for V = 0.5 and 0.9 $m.s^{-1}$ which showed that the flow-retarded region extended deeper, occupying approximately 50 and 70% of the flow depth, respectively, whereas for λ = 0.5, the retarded zone occupied only 30 and 45%, respectively. The Manning coefficient increased from 0.010 without water hyacinth to 0.0125 and 0.0149 with water hyacinth having a root depth of 5 and 30 cm, respectively.

Furthermore, an empirical formula of the water flow in an open channel with water hyacinth was developed. The water hyacinth effect coefficient (C_{hy}) was considered to be a function of plant density (λ) and plant root depth (h′). Finally, the flow velocity empirical formula was obtained and was shown to be in good agreement with the observed data in the verification process.

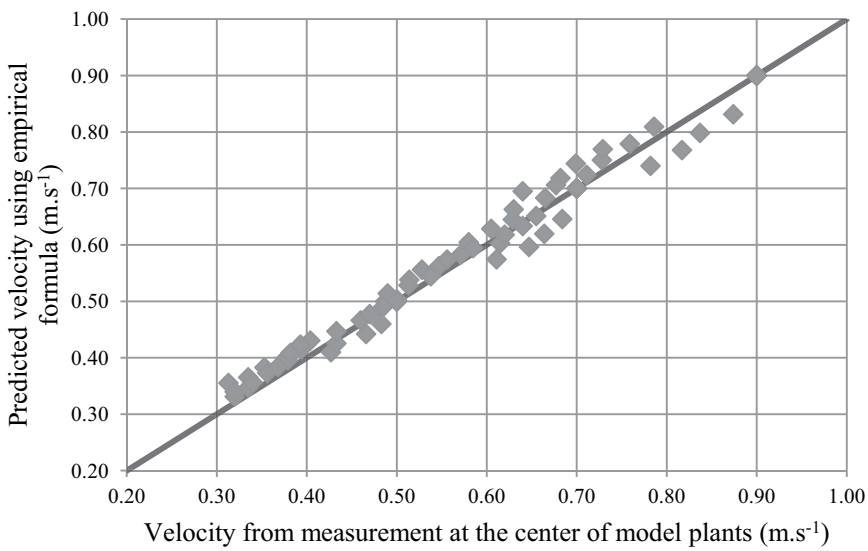


Figure 14 Comparison between average velocity calculated from Equation 4 and measured in the experiments.

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