Anisotropic flow resistance theory and experimental verification on partially submerged crop vegetation

Shengtang Zhang, Yin Liu, Jingzhou Zhang and Yuanchen Liu

ABSTRACT

The presence of orderly arranged rows and spacing of crop vegetation increases the anisotropy of the Earth's surface, and affects the resistance of the surface to overland flow. However, few studies have addressed how the orderly arrangement of crop vegetation affects the resistance of the surface to overland flow. In the present study, we consider that flow resistance has anisotropic attributes. We have also performed a flow resistance experiment using rigid and simulated partially submerged crop vegetation. The simulation replicated water flow in different directions over the same crop vegetation and overland surface. The angles of flow direction and the crop rows were arranged as 15 °, 30 °, 45 °, and 90 °. The results show that the flow resistance of partially submerged crop vegetation is composed of surface resistance n_s and vegetation resistance n_p. Vegetation resistance n_p is linearly proportional to the submerged vegetation height h, and the proportionality coefficient α ($\Delta n/\Delta h$) varies with the angle θ of the flow direction and the crop rows under the same water depth conditions, $n_{15} > n_{30} > n_{45} > n_{90}$. Further regression analysis revealed that the relationship between the coefficient α and vertical projection width of crop stems in the flow direction is a power function.

Key words | anisotropic property, crop vegetation, flow resistance, Manning roughness coefficient

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INTRODUCTION

With the increasing human population, a globally secure supply of food is urgently needed. Humans are modifying the slopes of an ever-increasing number of natural catchments by producing farmland on a global scale. The riverbanks of natural rivers, catchment slopes, and even shallow lakes have been converted into farmland. The creation of farmland changes the original characteristics and distribution of natural vegetation, slope, soil conditions, and resistance to overland flow, thereby changing the velocity and distribution of surface runoff in farming regions. The effects of farmland on overland flow will also change the response of runoff to rainfall, thereby drawing the attention of hydrologists. Hyväluoma *et al.* (2013) believed that tillage operations systematically produce small-scale surface roughness that may significantly modify the runoff patterns of cultivated areas. Commonly used flow-routing algorithms are not able to describe the effects of tillage-induced roughness. They introduced a flow-routing algorithm which accounts for anisotropic roughness resulting from tillage. Sepaskhah & Shaabani (2007) found that hydraulic and geometric parameters were different for anguiform furrow irrigation when compared with straight furrow irrigation. Manning's roughness coefficient in an anguiform furrow with a real flow path was lower than that in straight furrow irrigation. Takken & Govers (2001) suggested that a change in runoff from a farmland slope could be caused by a change in tillage direction.

In addition to the fact that farmland surfaces are different from the surfaces of slopes in natural catchments, large-scale crop vegetation will also produce different effects on water flow. Some research studies have discussed the effects

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of the distribution of vegetation on flow resistance. Nehal *et al.* (2005) suggested that overall flow resistance is significantly influenced by the pattern of distribution of vegetation. Luhar *et al.* (2008) explored how vegetation affects flow and transport as well as how flow feedbacks can influence the spatial structure of vegetation. Ye *et al.* (2015) believed that vegetation distribution patterns will modify the effects of resistance to overland flow. Tang *et al.* (2014) implied that friction caused by vegetation may be related to some other factors such as the physical arrangement and patterns of the vegetation.

Crop vegetation is generally arranged in orderly rows and plant spacing within rows. When compared with natural vegetation, the distribution of this cultivated vegetation creates different resistance effects on overland flow. However, little published literature on this subject has been found. This paper describes a flume experiment used to analyze the characteristics of the flow resistance caused by crop vegetation. We simulated water flow through crop vegetation in different directions using crop rows. The change of the flow resistance created by crop vegetation was analyzed under different slope and height-of-submergence conditions to reveal the effects of crop vegetation on flow resistance created in different directions. The goal was to help advance the development of physically based approaches that analyzed the resistance of vegetation to overland flow. This study will help researchers to understand the characteristics of the underlying surface in areas with agricultural cultivation, and different typical hydrological and hydraulic parameters associated with natural slopes and areas of agricultural cultivation in catchments. This study provides scientific background information of value in the study of farmland irrigation and flood control. At the same time, aquatic plants in wetland and lake shoal areas may exhibit certain patterns of distribution, and the presence of this vegetation may also have an effect on underlying roughness and related conditions (Grosh & Jarrett 1994). Therefore, this study also contributes to the prediction of how water flows in wetlands and lake shoal areas. Generally, most researchers have previously distinguished between partially submerged and submerged conditions. We focus on partially submerged vegetation because of our interest in tall stemmed crops, such as wheat, rice, and maize.

METHODS

The experimental setup employed an independent water circulation system, consisting of a pump, inlet, static pond, equalizing pipes, tail gate, electromagnetic flowmeter, recycling tank, and a flume. The flume was a smooth rectangular open channel with a glass side-wall 0.6 m high and was 0.4 m wide and 8 m long (Figure 1). In this experiment, the bed slope i of the flume could be adjusted from the end to simulate sloping farmland. A polymethyl methacrylate plate on with holes drilled in a matrix arrangement ($a \times b$ distance) covered the bottom of the experimental section. We inserted 15-cm-long plastic tubes into the drilled holes to simulate patterns and rows of crop vegetation (Figure 2). A recycled water tank supplied water for the experiment, simulating flooding of the farmland. Manometry tubes were set up to observe flow depth change along the flume. A discharge control valve was set after the water pump. During the experiment, the

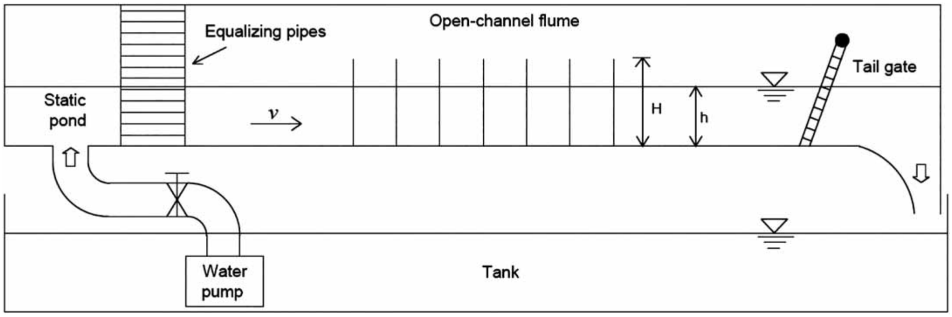

Figure 1 | Diagram of the experiment flume.

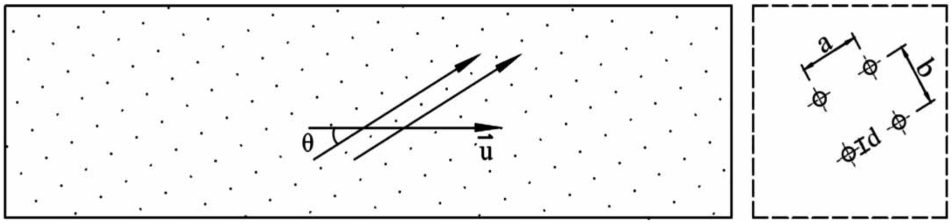

Figure 2 | Sketch of the flume bottom in the experiment with a 60 mm × 60 mm section showing the distribution of simulated crop vegetation: $\vec{u}$ is the flow direction and θ is the angle of the flow direction in relation to the crop rows within $a \times b$ spacing distribution; d is diameter of crop plant stem.

discharge Q, the angle θ of the flow direction and the crop rows, as well as the bed slope i were adjusted.

The flow depth h along the flume was observed and recorded when the flow passed through the experimental section under the different Q, θ and i conditions. The goal was to determine the effects of crop vegetation on flow resistance in a simple way; the bottom of the experimental section was designed so that vertical plastic tubes (60 mm × 60 mm) could be inserted in holes; these tubes were used to simulate the distribution of crop vegetation. The angle θ of flow direction and crop vegetation rows was set to vary at 15°, 30°, 45° or 90°, and the flume bed slope i was set to 0%, 0.5%, 1%, 1.5% or 2.0% (Figures 3 and 4). As with open-channel flow, the three most widely used equations used to evaluate the flow resistance include Manning's roughness coefficient n, the Chezy factor and the Darcy–Weisbach resistance coefficient f (Rouhipour *et al.* 1999; Hogarth *et al.* 2005; Smith *et al.* 2007). Among these, Manning's roughness coefficient n is considered essential for the accurate forecasting of rapid overland flooding. A flash flood is defined here as any flood that creates overland flow around the base of crops and completely covers the ground surface. Flash-flood flow is in the completely turbulent regime, meaning the Manning coefficient is applicable. Manning's roughness coefficient n is then determined by Equation (1):

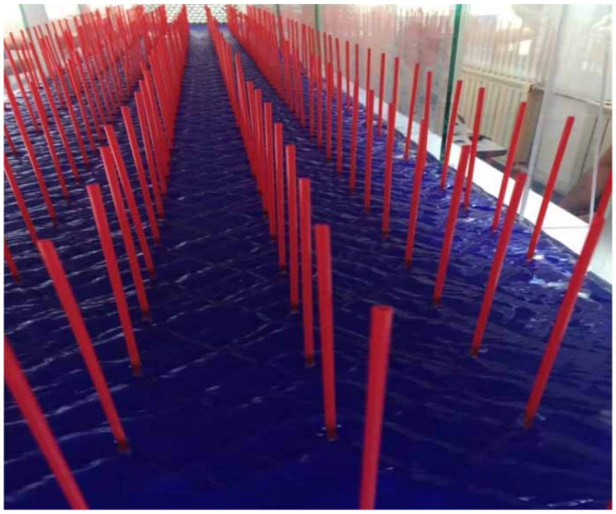

Figure 3 | Side view of the flume in 60 mm × 60 mm section, $\theta = 90°$, $i = 0.0\%$.

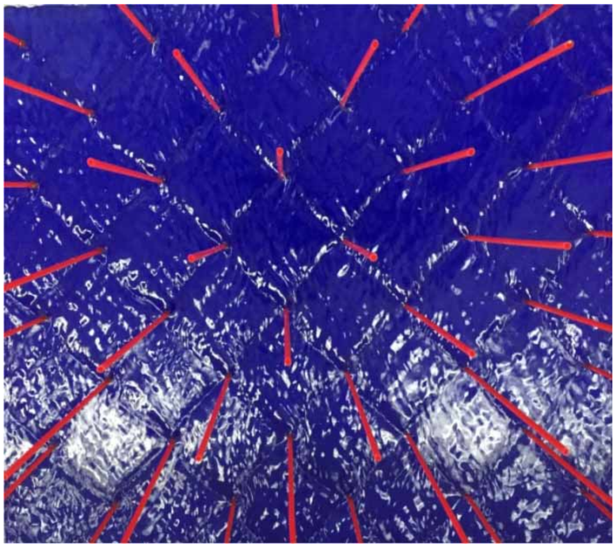

Figure 4 | Vertical view of the flume in 60 mm × 60 mm section, $\theta = 45°$, $i = 1.0\%$.

$$n = \frac{1}{v} R^{\frac{2}{3}} J^{\frac{1}{2}} \tag{1}$$

where R is the hydraulic radius, v is the mean flow velocity, and J is the hydraulic gradient.

Hydraulic experiments were performed on four different values of angle θ, five different i, and with an adjustable flow volume creating a total of 330 experimental data sets. The flume flow volume Q was observed by a model LDG-DN100 electromagnetic flowmeter (Hangzhou Meacon Automation Tech. Co., Ltd, Hangzhou, Zhejiang, China). The submerged height h of five cross-sections along the flume was recorded by the flume manometry tubes.

According to the observational data, the relationship between Manning's roughness coefficient n and the submerged height h was calculated and analyzed under the different θ and i. The effects of the slope on this relationship were considered as well. In the total of 330 experimental data sets, the ranges of hydraulic radius R, mean flow velocity v, flow discharge Q and hydraulic gradient J are 0.0025–0.0664 m, 0.0949–0.6266 m/s, 1.03–39.09 m^3/h and 0.0008–0.0247, respectively.

RESULTS AND DISCUSSION

Regression analysis of flow resistance for partially submerged crop vegetation

Based on the experimental data, the stippled value of Manning's roughness coefficient n changed with the crop vegetation submerged height h at different bed slope i according to the case of angle θ. There were four cases of angle θ (Figure 5).

The four parts of Figure 5 show that the relationship between points n and h from the five angles of bed slope is similar. Linear regression equations have high correlation coefficients with different θ as shown in Table 1.

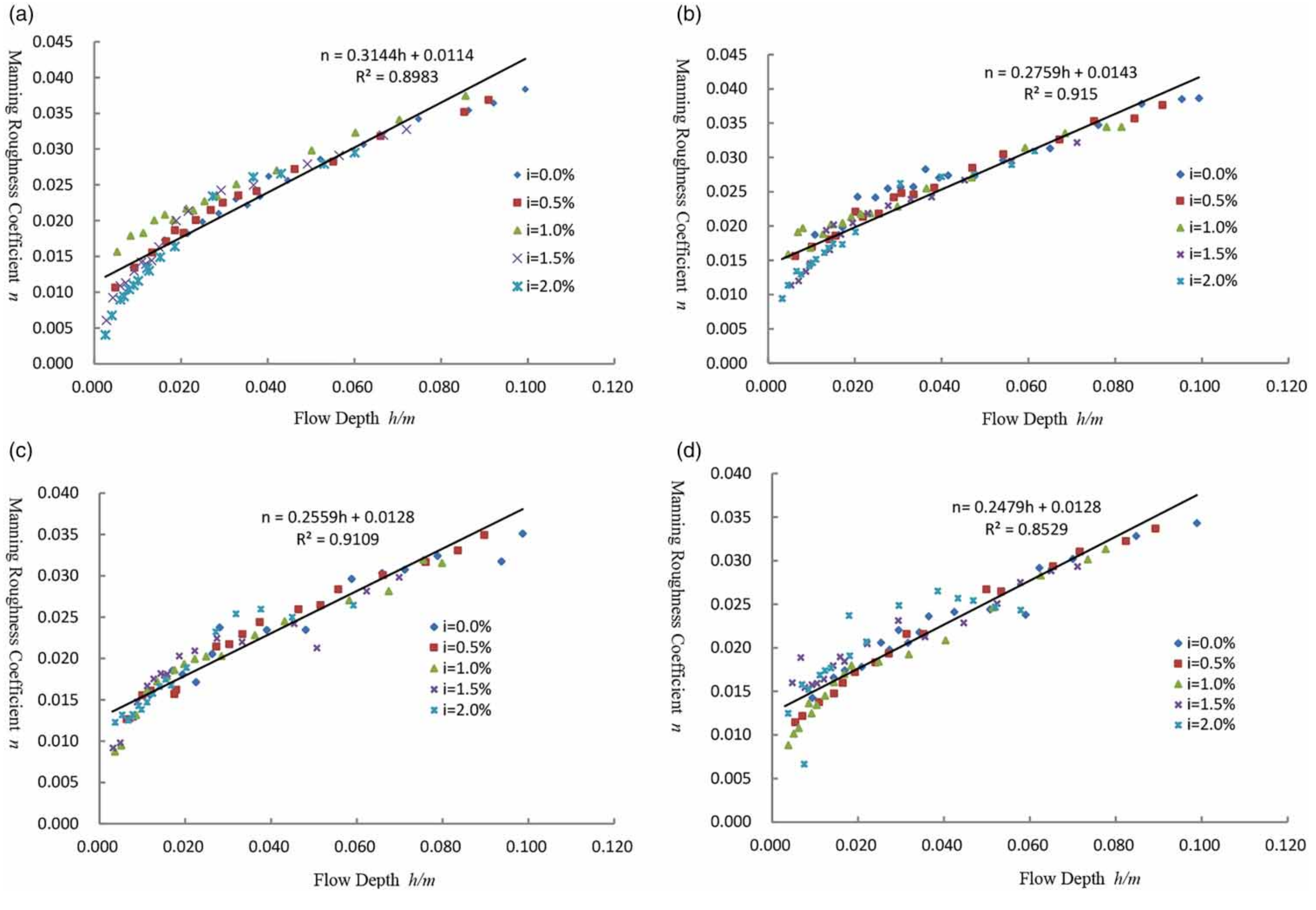

Figure 5 | The relationship of Manning's roughness coefficient n and height h under different values of angle θ of the flow direction and crop rows: (a) θ is 15°; (b) θ is 30°; (c) θ is 45°; (d) θ is 90°.

Table 1 | The parameters of different flow directions and angles of rows of partially submerged vegetation

Angle θ	Number of trails	Regression equations $n = \alpha h + \beta$			Plant stems projector width L/mm
		α	β	R^2	
90°	81	0.2479	0.0128	0.8529	20.00
45°	82	0.2559	0.0128	0.9109	28.29
30°	85	0.2759	0.0143	0.9150	40.00
15°	82	0.3140	0.0114	0.8983	77.28

The combined effects of partially submerged crop vegetation on flow resistance

The four regression equations have the same form, as seen in Equation (2):

$$n = \alpha h + \beta \tag{2}$$

where α is the proportionality coefficient, $\alpha = \Delta n/\Delta h$, and β is a constant in each equation; when θ is 15°, 30°, 45°, and 90°, then β is 0.0114, 0.0143, 0.0128, and 0.0128, respectively. Theoretical analysis can show that the contribution of crop vegetation to n will be zero if h tends to zero. That means that the constant β becomes equal to n on a bare soil surface without any vegetation at all. Jin *et al.* (2000) and Jeon *et al.* (2014) also have similar ideas related to the flow resistance of partially submerged vegetation. Following this idea, the plastic tubes which were inserted to simulate crop vegetation were removed with only the polymethyl methacrylate plate paving the channel bed. The Manning roughness coefficient n_s was tested under three slope conditions of $i = 0.0\%$, 0.5%, 1.0%. In this case, Figure 6 shows the relationship between n_s and h, based on the present experiment.

Clearly, based on Figures 5 and 6, n of the polymethyl methacrylate plate (no plastic tubes simulating vegetation) remains steady in the range from 0.0091 to 0.0160, and does not change significantly with variations in flow depth. Moreover, the average value of n when using only the polymethyl methacrylate plate, which was obtained using three slope angles in 38 sets of experimental data, was 0.0124.

Therefore, not only the range but also the average of the plate n agrees with the value of the constant term β in the regression equations. That is, the slope has little effect on the relationship between n_s and h, but why and how it affects these variables remains unknown.

Theoretical analysis and experimental results can verify the following theory: the flow resistance of partially submerged crop vegetation is composed of two parts; one part is the flow resistance that is induced from every individual plant of crop vegetation (n_p), while the other part is flow resistance of the bare soil surface (n_s). Several previous studies (Parsons *et al.* 1994; An & Liu 2011; Jiang *et al.* 2012) have suggested that the resistance of overland flow can be a linear combination of several components. Following their ideas, the formula can be written as Equation (3) when n is chosen to address the flow resistance:

$$n = n_p + n_s \tag{3}$$

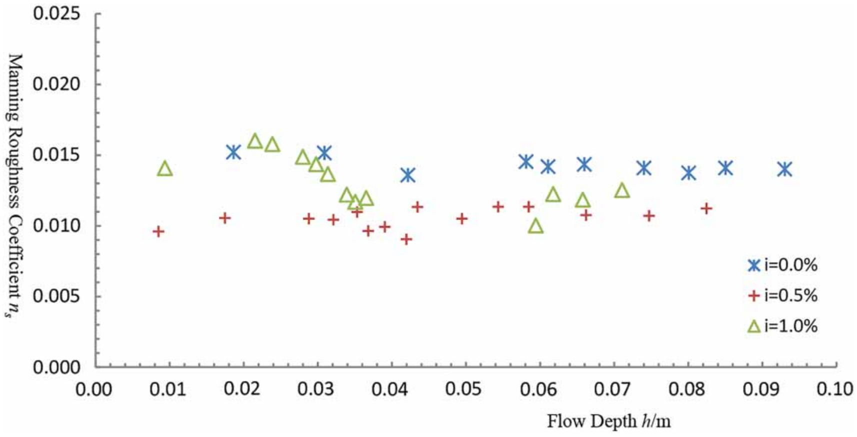

Figure 6 | Relationship of the Manning roughness coefficient n and flow depth h with no simulated vegetation.

Variation in flow resistance of partially submerged crop vegetation with changes in flow direction

The regression equations show that n and h have a linearly proportional relationship under every θ condition, and they have a very high correlation coefficient. This matches the results of previous relevant literature (Järvelä 2004; Roche *et al.* 2007; Wang *et al.* 2012).

However, the proportional value of the linear relationship between n and h varies with change of θ. This means that increases or decreases of n for the same partially submerged vegetation with an increase or decrease per unit h will change according to the direction of the water flow through the crop vegetation. That is, for the same partially submerged crop vegetation with the same h, when the water flow through the crop vegetation varies in direction, the flow resistance of the crop vegetation will be different. Therefore, the crop vegetation with orderly arranged rows and plant spacing within rows has an anisotropic flow resistance when partially submerged. This anisotropic characteristic of flow resistance has been addressed in some of the literature; for example, Stephan & Gutknecht (2002) indicated that the conventional Manning formula is one-dimensional and based on integral flow parameters. It is not suitable for quantifying the roughness of the complex and more dimensional flow due to the variable behavior of the plants. Velasco *et al.* (2003) suggested anisotropic Reynolds tensors. Strellkoff *et al.* (2003) presented the tensor flow resistance model based on the original Manning's roughness formula and potential energy theory, which is used to describe the anisotropic roughness features of catchment surfaces. Zhang *et al.* (2005) proposed the vector roughness theory.

The angle θ of flow direction and the effects of crop vegetation rows affect the rate of change in α ($\alpha = \Delta n/\Delta h$) for specific n and h, and θ is a factor that affects α. The functional relationship can be written as $\alpha = f(\theta)$.

Further analysis shows that, for the same arrangement of rows and plant spacing within rows (60 mm × 60 mm) of crop vegetation with the same h, the value of n for partially submerged crop vegetation with a different angle θ can be ranked $n_{15} > n_{30} > n_{45} > n_{90}$. The n characterizes the flow resistance of the solid boundary to water flow. If h is held constant, the area of the water contact solid boundary will also be constant, and the solid boundary materials are also the same in the entire experiment (glass wall, polymethyl methacrylate plate bed, and plastic tubes). The only changed element is the projected area of crop vegetation in the vertical plane of the flow direction when θ changes. Because h is held constant, when θ changes, the vertical projection width L of crop vegetation in the vertical plane of the flow direction is changed. The L is an index of crop plant stems occupying the cross-sectional area of water flow. Obviously, L changes with any variation in θ, as seen in Equation (4):

$$L = \left(\frac{B}{a \sin\theta}\right) d \tag{4}$$

where L is the vertical projection width of the plant stem, B is the flume width, a is the spacing between the plants, d is the plant stem diameter, and θ is the angle of the flow direction and the crop rows. In some cases, the value of θ in Equation (4) can be the co-angle of the experiment angle because L is the vertical projection width of the plant stem, and the row will change to a column when the angle changes.

In the experiment, d is 3 mm, a is 60 mm, B is 400 mm, and θ varies (15 °, 30 °, 45 °, and 90 °). Table 1 shows the parameters of the specific angles. Figure 7 shows the regression analysis of the relationship between L and α.

The result of the regression analysis shows that the relationship between L and α is a power function, and these two variables are strongly correlated. When the flow resistance of the partially submerged crop vegetation is

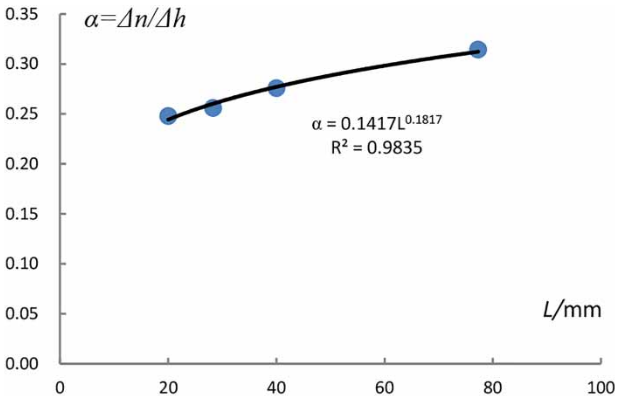

Figure 7 | The regression equation of the vertical projection of stem width L and the proportionality coefficient α.

characterized by n, the rate of variation of n with the change of h exhibits a power function relationship with the projected width L of the crop vegetation in the vertical plane of the flow direction. Given the distribution of the crop vegetation and crop types, a change in θ will lead to variation in L, and the rate of change of α for n with h varies with a change in L. Therefore, in the same flow and crop vegetation conditions, changes in the value of θ will actually result in an indirect change in n. In other words, the partially submerged crop vegetation has a different flow resistance when the flow comes from different directions, and the relationship can be shown in Equation (5):

$$n_{\mathrm{p}} = 0.1417L^{0.1817}h \tag{5}$$

Further analysis of Equations (4) and (5) shows that plant spacing has effects on flow resistance. Given B, d and θ, the increase of plant spacing of partially submerged crop vegetation will lead to a decrease of projected width L of the crop vegetation, and finally lead to a decrease of flow resistance.

CONCLUSIONS

Large-scale farmland that replaces natural vegetation will affect the characteristics of overland flow in catchments. The distribution of crops in rows and plant spacing within rows will change the hydraulic characteristics of overland runoff flowing through the vegetation. This paper focuses on the effects of partially submerged crop vegetation on the flow resistance of flash floods in a farmland region. Flash floods generally exhibit a completely turbulent regime, so the Manning roughness coefficient n is used to characterize the flow resistance of partially submerged crop vegetation. Through a total of 368 experimental simulations, the following conclusions are drawn.

1. The flow resistance of partially submerged crop vegetation and the submerged height has a linearly proportional relationship, with a very high correlation coefficient. This matches the research results published in previous relevant literature.
2. The flow resistance of partially submerged crop vegetation is composed of two parts; one part is flow resistance induced by every individual plant of the crop vegetation, while the other part is flow resistance of the bare soil surface.
3. Crop vegetation is typically arranged regularly in rows and with regular plant spacing within rows, resulting in an increase in the anisotropy of surface features. That is, flow resistance in crop vegetation has anisotropic attributes. For the same arrangement of rows and plant spacing within rows for crop vegetation with the same submerged height, the n of partially submerged crop vegetation with different angles of flow direction and crop rows can be ranked $n_{15} > n_{30} > n_{45} > n_{90}$.
4. The rate of change in flow resistance in different directions in relation to the submerged height was found to be strongly correlated to the projected width of crop vegetation plant stems in the vertical plane of the flow direction, and follows a power law relationship.

In reality, catchments are complex and changeable, while the distribution patterns of crop vegetation vary; meanwhile, individual plants have different morphological characteristics, such as the number and sizes of leaves and branches. Flow itself can occur in different regimes. Often, vegetation is also likely to be completely submerged. The results of the paper only represent laboratory conditions. The results will vary from the conditions in actual catchments, and how the experiment can be modified and used in actual catchments will be a topic of further study.

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