The resistance effect of vegetation stem diameter on overland runoff under different slope gradients

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ABSTRACT

Vegetation is an important part of the natural environment and has resistance effects on overland runoff, which can effectively reduce hydraulic erosion. The effect of vegetation stem diameter and slope gradient on flow resistance is thus worthy of further study. The influence of three different slope gradients (*s*), three vegetation stem diameters (*d*) and 12 levels of unit discharge (*q*) on the flow resistance of a slope was simulated to systematically study the effect of vegetation stem diameter and slope gradient on overland runoff. The diameter of the vegetation stem and the slope gradient were found to have a significant resistance effect on overland runoff. Under the same slope gradient, the Darcy–Weisbach resistance factor (*f*) increased with an increase in the vegetation stem diameter. Under experimental conditions, the rate of change of *f* was analysed by linear regression, and as *d* increased by 1 mm, *f* increased by an average of 49.9%. For a given vegetation stem diameter and vegetation distribution pattern, the greater the slope gradient, the smaller the value of *f*, and as *S* increased by 1.0%, *f* decreased by an average of 24.5%. These results are important to optimize the slope vegetation distribution in farmland conservation.

Key words | flow resistance, overland runoff, slope gradient, vegetation stem diameter

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INTRODUCTION

Soil erosion, which is one of several major environmental and land degradation problems worldwide, threatens global agricultural production and food security. Vegetation plays an irreplaceable role in the natural environment and is an important part of the ecosystem (Boer & Puigdefábregas 2005; Zhou & Shangguan 2007; Ding & Li 2016). The existence of slope vegetation has a retardation effect on overland runoff (Gabarrón-Galeote *et al.* 2013; Konečná *et al.* 2014; Lieskovský & Kenderessy 2014), so vegetation can effectively reduce soil erosion. As a result, vegetation is widely used for slope protection, soil and water conservation, and other aspects of hydraulic design. There are numerous vegetation characteristics that affect overland runoff, for example, topographic features, soil texture, vegetation cover density and type, and rainfall intensity and duration (Folkard 2011; Shucksmith *et al.* 2011; Li *et al.* 2018). The study of vegetation effects on overland runoff is complicated by these factors, and the flow resistance characteristics of vegetation require further analysis.

To date, numerous studies have been conducted on the effects of vegetation on flow resistance. For example, Järvelä (2005) studied the effects of vegetation flexibility on water resistance by selecting flexible vegetation and rigid vegetation. The results indicated that different vegetation flexibility levels exerted different levels of resistance to flow. Yagci *et al.* (2010) studied the effects of non-submerged vegetation on water structure and kinetic energy characteristics using pineapple branches as experimental materials. Zhang *et al.* (2012) found that the irregular distribution of vegetation had a significant effect on the slowing of flow velocity. In addition, Zhao *et al.* (2015) argued that when vegetation is present on a slope, the vegetation roots can effectively reduce the sediment transport capacity and thus reduce soil erosion. Ding & Li (2016) showed that the distribution of vegetation in the lower part of a test section was better than that in the middle and upper parts, and the vegetation distribution pattern had an important influence on the hydraulic characteristics of the slope.

Based on the above literature, it can be seen that the current research on the flow resistance of vegetation has mainly focused on the vegetation type, the vegetation

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distribution, and the flow regime in which the vegetation occurs. However, as time progresses, even if the same vegetation is present on the slope surface, the stem roughness changes constantly during different growth stages. In addition, with the development of human society, natural slopes are often affected by human activities (such as afforestation), and these artificial plantations result in regular vegetation distribution, especially as the selected nursery specifications are uniform. Although the effects of a rigid vegetation stem diameter on flow resistance have been considered in some studies, a complete system of experimental research and quantitative analysis is currently lacking. Flood flow and irrigation flow between plants are greatly affected by vegetation stem diameter. In this study, the flow resistance of different vegetation stem diameters under different slope gradient conditions was examined.

METHODS AND MATERIALS

Design of the experimental installation

Overland runoff has mainly been researched in open channels. Some flow formulas and theories have been reported in recent decades. Many scholars used a variable gradient flume to conduct experimental research. In these studies, a cylinder was used to simulate the vegetation (Li & Shen 1973; Dunn *et al.* 1996).

In order to study the effect of vegetation stem diameter on overland flow resistance, a water flow system was adopted in this experiment. The experimental device was a rectangular flume with a length of 5 m, a width of 0.4 m, and a depth of 0.3 m (Figure 1). The device was set for a variable slope test and was composed of a tank, sink, water pump, static pond, equalizing pipes, manometry tubes, and a tail gate. The sink was divided into three parts: an equalizing section, middle test section, and an end gate section. There was a flow control valve at the connection between the tank and the sink. The unit discharge (q) range was 0–0.028 m^3/s. A polymethyl methacrylate board used to simulate the distribution of vegetation was placed on the bottom of the middle test section. Through field observation and analysis of the distribution of overland vegetation, the vegetation was quantified, and the height was measured, in addition to the diameter of the stem, the spacing between the plants, and other characteristic parameters. Then, the hydraulic similarity principle was used to simulate the vegetation on the slope, and a hydraulic model was established to carry out the experiment on the vegetation resistance of the slope flow in the laboratory. The board had holes drilled with row spacing of 60 mm. Cylindrical plastic pipes were inserted into the holes to simulate vegetation stems (Figure 2). To ensure the accuracy of the test, we used three different diameter (d) plastic cylindrical rods ($d = 3$, 4, and 5 mm) to simulate the stems of the vegetation. The experimental boards are shown in Figure 3. A pump circulated the water during the experiment.

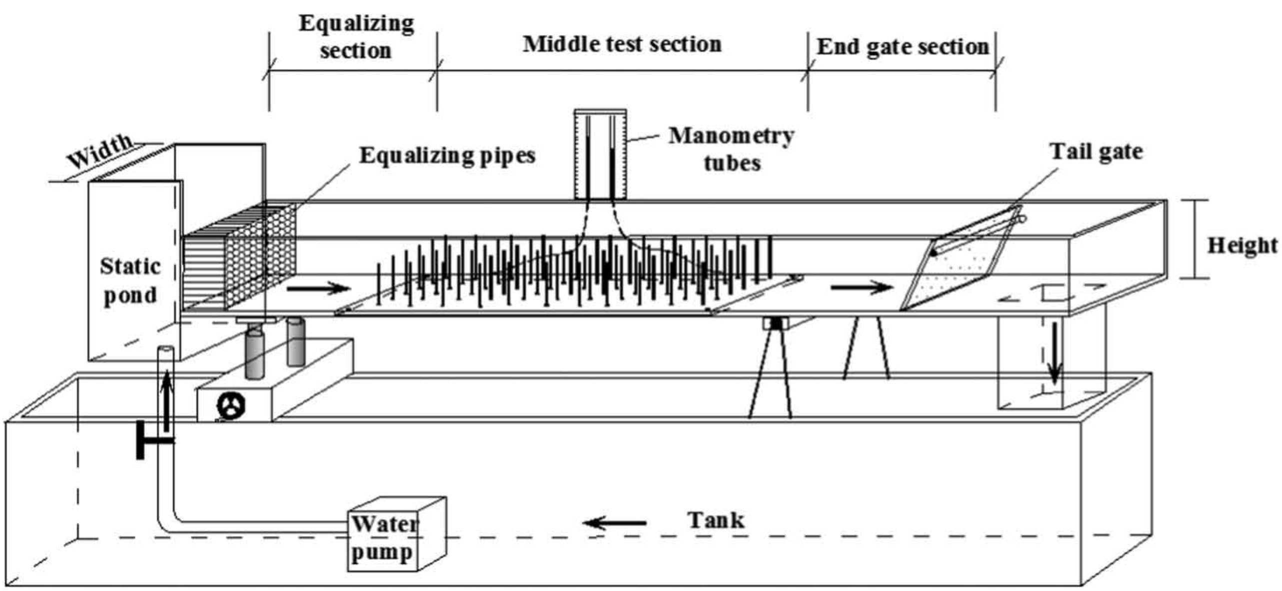

Figure 1 | Diagram of the experiment device.

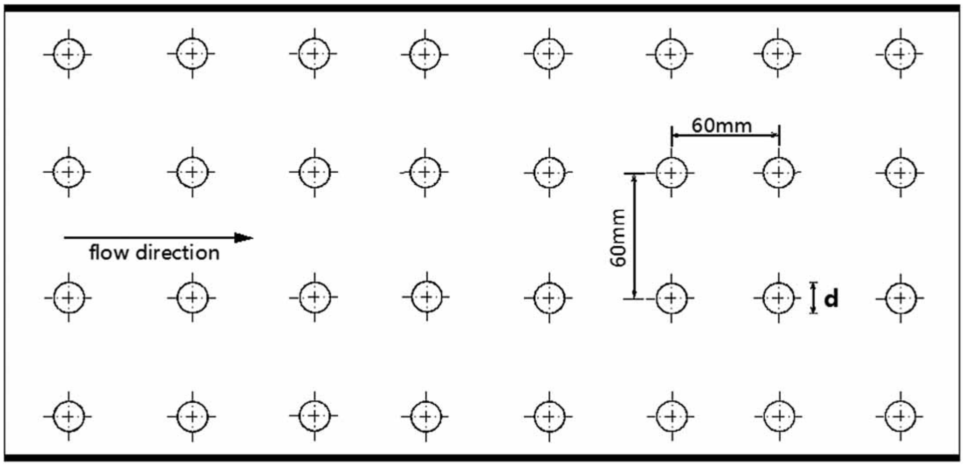

Figure 2 | Experiment floor plan.

Figure 3 | Photographs of the experimental setup for different vegetation stem diameters.

Hydraulic parameter calculation

Overland runoff is typically analyzed by measuring flow properties, flow velocity, erosion caused by flow, and sediment transportation. Two important hydraulic parameters are the Reynolds number (*Re*) and Froude number (*Fr*) (Woolhiser *et al.* 1970; Sidorchuk *et al.* 2008).

The essential parameter *Re* is used to reflect flow patterns. It represents a ratio of the inertial force of a viscous fluid flow to the viscous force and can be calculated using Equation (1):

$$Re = \frac{VR}{v} \quad (1)$$

where V is the water velocity; v is the motion viscosity coefficient; and R is the hydraulic radius.

The mechanical significance of *Fr* is used to analyze the ratio of the inertial force of flow to gravity. From an energy perspective, *Fr* represents the ratio of average kinetic energy per unit weight of a liquid to the average potential energy. The calculation of *Fr* for open-channel flow is shown in Equation (2):

$$Fr = \frac{V}{\sqrt{gh}} \quad (2)$$

where h is the water depth, and g is the acceleration caused by gravity.

The resistance to flow refers to the slowing of flow caused by the roughness of the land surface and vegetation. Resistance coefficients reflect the degree of resistance caused by the underlying surface of watersheds on flow. The Darcy–Weisbach resistance factor (f) is applicable to both laminar and turbulent regimes and has a high physical significance (Luo *et al.* 2009). Therefore, it was adopted to represent the flow resistance caused by vegetation using Equation (3):

$$f = \frac{8h_f Rg}{LV^2} \quad (3)$$

where h_f is the energy loss along the experimental section, L is the length of the experimental section, and R is the hydraulic radius.

To analyze the effects of vegetation stem diameter on the resistance to flow, 108 experiments were conducted at the three different stem diameters. The vertical and horizontal spacing between the vegetation types was 60 mm × 60 mm (Supplementary Tables 1–3, available with the online version of this paper).

RESULTS AND DISCUSSION

Effects of vegetation stem diameter

The f-h curve was drawn according to the experimental data (Figure 4). The increase in f as h increased was obtained under three different slope conditions. This is consistent with the conclusion that the relationship between f and h in Zhang *et al.* (2017) and Järvelä (2002) was based on the influence of vegetation distribution on slope flow resistance.

For the three different slopes of the f-h relationship diagram, under the same water depth, the larger the diameter of the vegetation stem, the larger the f value: $f_{5\text{ mm}} > f_{4\text{ mm}} > f_{3\text{ mm}}$. This indicates that the change in the vegetation stem diameter had an obvious influence on f. Vegetation with a larger stem diameter had a much greater friction effect on the water flow. This conclusion is similar to that of previous researchers (Pan & Shangguan 2006; Al-Hamdan *et al.* 2012; Zhao *et al.* 2015).

To quantitatively study the effects of vegetation stem diameter on the water resistance of the slope, the hydraulic

Table 1 | Interpolation data on water depth h and Darcy-Weisbach resistance factor f and the effect of vegetation stem diameter d on the change rate of Darcy-Weisbach resistance coefficient f in each slope gradient (S is 0.0%, 1.0% and 2.0%, respectively)

		Interpolation number (n)					
Slope gradient	**Parameter**	**1**	**2**	**3**	**4**	**5**	**6**
$S = 0.0\%$	h (m)	0.02	0.03	0.04	0.05	0.06	0.07
	$f_{d=3\text{ mm}}$	0.0911	0.1078	0.1395	0.1392	0.1454	0.1844
	$f_{d=4\text{ mm}}$	0.0972	0.1744	0.1858	0.2519	0.2585	0.2610
	$f_{d=5\text{ mm}}$	0.1658	0.2096	0.2311	0.3511	0.3532	0.3810
	$(f_{4\text{mm}}\text{-}f_{3\text{mm}})/f_{3\text{mm}}$	6.67%	61.68%	33.17%	80.94%	77.79%	41.51%
	$(f_{5\text{mm}}\text{-}f_{4\text{mm}})/f_{4\text{mm}}$	70.52%	20.22%	24.41%	39.40%	36.64%	46.00%
$S = 1.0\%$	h (m)	0.02	0.03	0.04	0.05	0.06	0.07
	$f_{d=3\text{ mm}}$	0.0957	0.0951	0.0967	0.1098	0.1459	0.1780
	$f_{d=4\text{ mm}}$	0.1460	0.1417	0.1533	0.2187	0.2328	0.2732
	$f_{d=5\text{ mm}}$	0.2121	0.2277	0.2512	0.2821	0.2991	0.3290
	$(f_{4\text{mm}}\text{-}f_{3\text{mm}})/f_{3\text{mm}}$	52.56%	48.99%	58.57%	99.15%	59.53%	53.46%
	$(f_{5\text{mm}}\text{-}f_{4\text{ mm}})/f_{4\text{mm}}$	45.27%	60.69%	63.84%	28.99%	28.46%	20.42%
$S = 3.0\%$	h (m)	0.01	0.015	0.02	0.025	0.03	0.035
	$f_{d=3\text{ mm}}$	0.0713	0.0834	0.0834	0.0806	0.1380	0.0973
	$f_{d=4\text{ mm}}$	0.1335	0.1256	0.1179	0.1489	0.1649	0.1831
	$f_{d=5\text{ mm}}$	0.1456	0.1476	0.1955	0.2320	0.2616	0.2925
	$(f_{4\text{mm}}\text{-}f_{3\text{mm}})/f_{3\text{mm}}$	87.14%	50.61%	41.37%	84.75%	19.55%	88.18%
	$(f_{5\text{mm}}\text{-}f_{4\text{mm}})/f_{4\text{mm}}$	9.09%	17.48%	65.71%	55.82%	58.60%	59.69%

Table 2 | Interpolation data on unit discharge q and Darcy-Weisbach resistance factor f and the effect of slope gradient S on the change rate of Darcy-Weisbach resistance factor f in each vegetation stem diameter distribution (d is 3 mm, 4 mm and 5 mm, respectively)

		Interpolation number (n)					
Diameter	**Parameter**	**1**	**2**	**3**	**4**	**5**	**6**
$d = 3$ mm	q (m^3/s)	0.00075	0.00100	0.00125	0.00150	0.00175	0.00200
	$f_{s=0.0\%}$	0.1395	0.1390	0.1542	0.1884	0.2111	0.1993
	$f_{s=1.0\%}$	0.0967	0.0954	0.0995	0.1236	0.1694	0.1467
	$f_{s=2.0\%}$	0.0789	0.0863	0.0810	0.0841	0.0857	0.0815
	$(f_{1.0\%}\text{-}f_{0.0\%})/f_{0.0\%}$	−30.70%	−31.42%	−35.48%	−34.39%	−19.74%	−26.40%
	$(f_{2.0\%}\text{-}f_{1.0\%})/f_{1.0\%}$	−18.36%	−9.54%	−18.56%	−31.95%	−49.41%	−44.45%
$d = 4$ mm	q (m^3/s)	0.00075	0.00100	0.00125	0.00150	0.00175	0.00200
	$f_{s=0.0\%}$	0.1727	0.2412	0.2580	0.2608	0.2844	0.2674
	$f_{s=1.0\%}$	0.1415	0.1699	0.1416	0.2149	0.2396	0.2570
	$f_{s=2.0\%}$	0.1249	0.1157	0.1111	0.1291	0.1410	0.1960
	$(f_{1.0\%}\text{-}f_{0.0\%})/f_{0.0\%}$	−18.06%	−29.57%	−45.09%	−17.60%	−15.76%	−3.89%
	$(f_{2.0\%}\text{-}f_{1.0\%})/f_{1.0\%}$	−11.73%	−31.89%	−21.54%	−39.94%	−41.15%	−23.76%
$d = 5$ mm	q (m^3/s)	0.00075	0.00100	0.00125	0.00150	0.00175	0.00200
	$f_{s=0.0\%}$	0.2809	0.3625	0.3505	0.3615	0.4110	0.4548
	$f_{s=1.0\%}$	0.2254	0.2491	0.2826	0.3135	0.2862	0.3277
	$f_{s=2.0\%}$	0.1798	0.1930	0.2309	0.2542	0.2742	0.3137
	$(f_{1.0\%}\text{-}f_{0.0\%})/f_{0.0\%}$	−19.75%	−31.29%	−19.36%	−13.28%	−30.38%	−27.94%
	$(f_{2.0\%}\text{-}f_{1.0\%})/f_{1.0\%}$	−20.22%	−22.53%	−18.32%	−18.92%	−4.16%	−4.27%

parameter values (f) were obtained by a numerical interpolation method under the same water depth condition for three different slope gradients, and the change in f was determined using linear regression analysis (Table 1). Under the same experimental water depth conditions, the results showed that as d increased by 1 mm, f increased by an average of 49.9%.

To systematically study the intrinsic relationship between stem diameter d and f, the slope gradient $S = 1.0\%$ was used to analyze the influence of the diameter of the vegetation on the flow regime because the flow regime reflects the change in the flow resistance.

At a constant water depth, smaller d values were observed to correspond with larger Re values, such as $Re_{3\ mm} > Re_{4\ mm} > Re_{5\ mm}$ (Figure 5(b)). The results indicated that a smaller d value was observed when the solid boundary containing plant stems had less effect on the water flow. Moreover, the effect of the inertial force of the water flow was larger when d was smaller. The inertial force played a greater role than the viscous force. The level of turbulence of the water flow was also larger when d was smaller. When the water depth was constant, smaller d values were also observed, corresponding to larger Fr: $Fr_{3\ mm} > Fr_{4\ mm} > Fr_{5\ mm}$ (Figure 5(c)). The results indicate that kinetic energy played a greater role in the mechanical energy of the water flow than potential energy when the value of d was relatively small. As d increased, the resistance to water flow increased. At a larger d, extra kinetic energy of the water flow was consumed, causing the velocity of the water flow to decrease (Figure 5(a)). It can be concluded from Figure 5(b) and 5(c) that the flow state of the water flow was mainly distributed in the three major flow regions of the slow transition flow region, the rapid transition flow region and the rapid turbulent flow region. When the water depth was shallow, the flow pattern of the water flow was relatively stable, and the test points of the three different vegetation stem diameters were distributed in the transition flow region. As the water depth increased, the flow state extended from the transition flow region to the turbulent flow region. This resulted in a decline in the level of turbulence in the flow of the water. Analysis of a single plant indicated that with an increase in plant stem diameter, the cross-sectional area of the plant in the water increased so that the actual cross-sectional area of the water

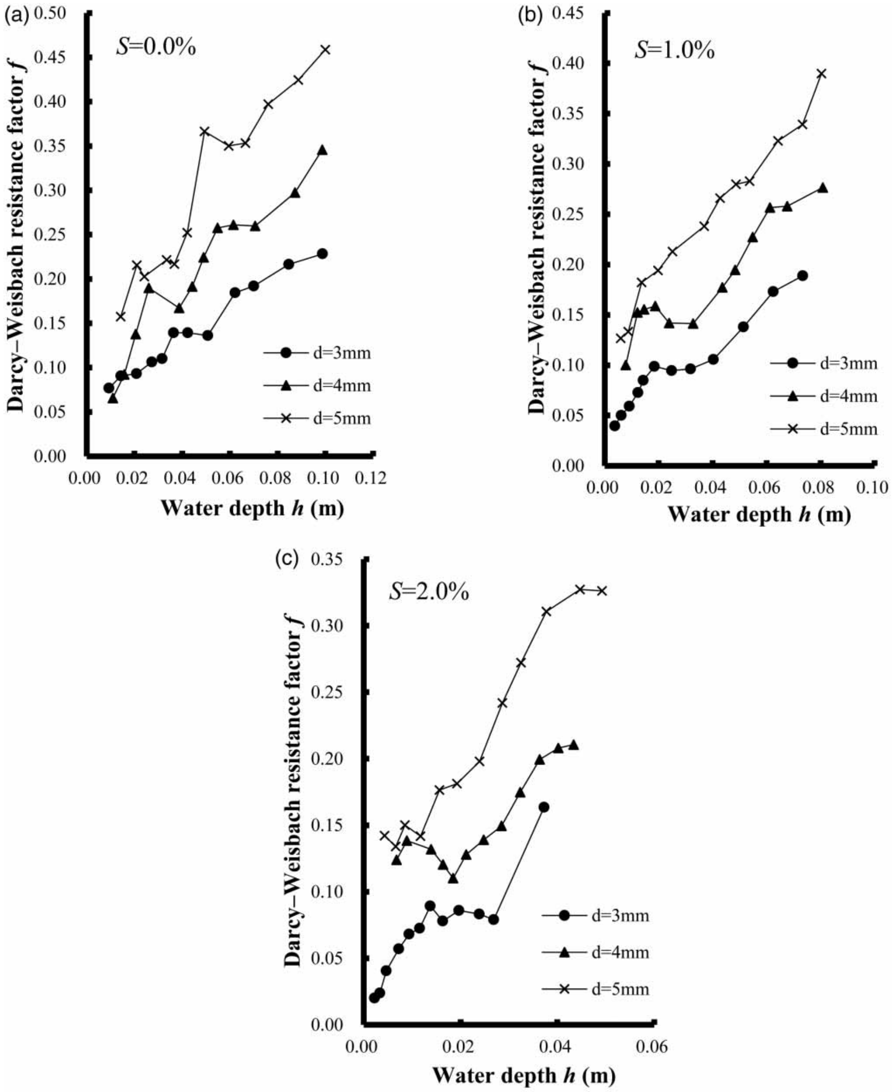

Figure 4 | Curve of Darcy-Weisbach resistance factor *f* and water depth *h* for three vegetation stem diameters under different slopes gradients.

flow was reduced. As a result, the wetted perimeter of water flow through the vegetation increased, causing the friction between the water flow and vegetation to increase. The resistance to water flow therefore increased with increasing *d*.

Effect of slope gradient

In order to study the effect of different slope gradients on flow resistance, we plotted the *f*-*q* curve from the experimental data (Supplementary Tables 1–3, available with the online version of this paper). Under the three different vegetation stem diameters, *f* under different slope gradients increased with increasing *q* (Figure 6), which is consistent with the study conclusions of Pan & Shangguan (2006) and Zhao *et al.* (2015).

Under the same *q*, *f* decreased with an increase in the slope gradient: $f_{0.0\%} > f_{1.0\%} > f_{2.0\%}$. When $q < 0.005\ m^3/s$, the degree of the decrease in *f* with increasing slope gradient was not clear. When $q > 0.005\ m^3/s$, the degree of decrease in *f* with increasing slope gradient was more obvious. It can be concluded that the slope gradient is an important factor that affects the flow resistance of overland runoff.

To quantitatively study the effects of slope gradient on the water resistance of the slope, the hydraulic parameter values (*f*) were obtained by a numerical interpolation method under the same unit discharge condition for three different vegetation stem diameters, and the change in *f* was determined using linear regression analysis (Table 2). Under the same experimental unit discharge conditions,

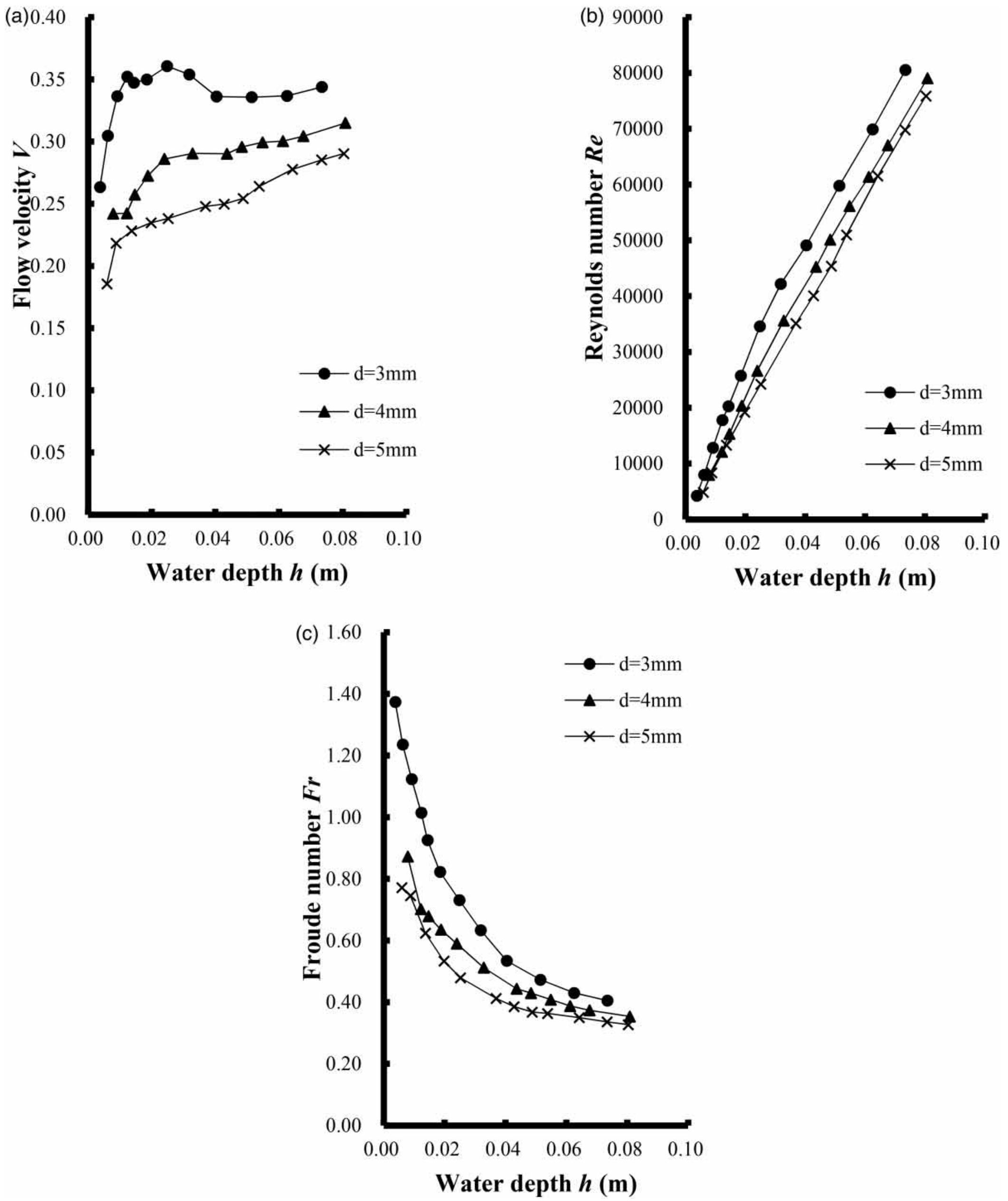

Figure 5 | Relationships among (a) flow velocity *V* versus water depth *h*, (b) Reynolds number *Re* versus water depth *h*, (c) Froude number *Fr* versus water depth *h* of three vegetation stem diameters under slopes gradient is 1.0%.

the results showed that as *S* increased by 1.0%, *f* decreased by an average of 24.5%.

CONCLUSION

Overland runoff or irrigation flow on the land surface causes soil erosion. Systematic study of the vegetation stem diameter effects on overland runoff is required to reduce the erosion capacity and to control the hydraulic erosion of overland runoff. In this experiment, a variable slope flume was used to simulate the surface flow of slope vegetation under three different slope gradients and three different vegetation stem diameters. The results show that:

(1) As *h* increased, *f*, *v*, and *Re* increased and *Fr* decreased.
(2) The vegetation stem diameter had a significant effect on the flow resistance. Under the three different slope

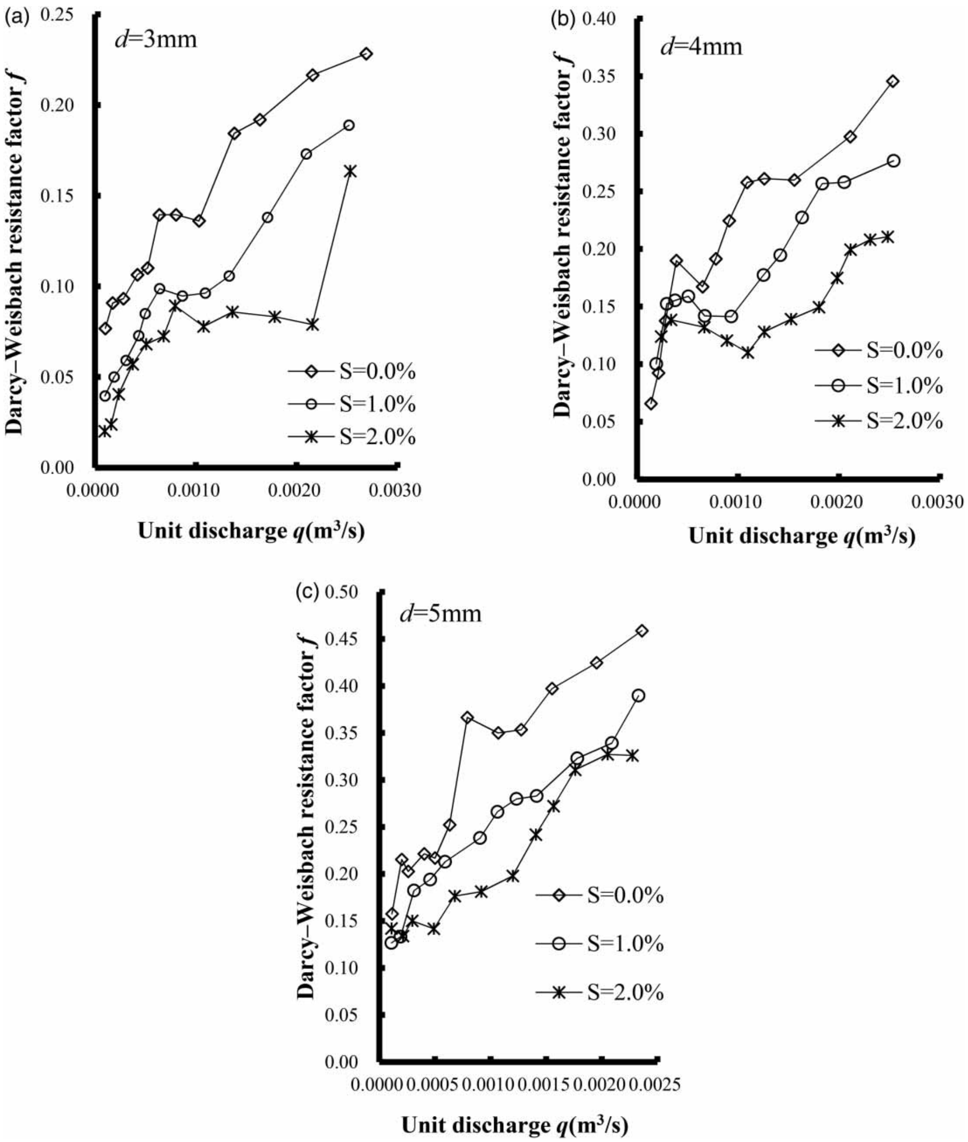

Figure 6 | Curve of Darcy-Weisbach resistance factor *f* and unit discharge *q* for three slope gradients under different stem diameters.

gradients, the larger the vegetation stem diameter, the larger the value of *f*.

(3) The slope gradient is one of the most important factors that affect the flow resistance of watersheds. Under the same *q*, the *f* value decreased with increasing slope gradient.

It should be pointed out that this conclusion is based on the control of other factors. Due to the effects of the watershed vegetation distribution, micro-terrain, soil characteristics and other factors, the actual flow resistance caused by vegetation is extremely complex. The reliability and adaptability of the findings of this study should be further studied.

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