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Simulation Study of Anisotropic Flow Resistance of Farmland Vegetation

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Abstract

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Farmland vegetation is commonly cultivated with uniform planting spacing and heights. The effect of these features on resistance to hydraulic erosion is unclear. Hydraulic model experiments with the angle between the crop rows and the water flow direction set at 15°, 30°, 45° or 90° were conducted to analyze variation in the law of water flow resistance under partial or complete submergence of the crop. Cultivation can impact the flow resistance on slopes and this effect was greater when the crop was partially submerged. When planting spacing, slope, and water depth were constant, the change of the water flow Darcy-Weisbach resistance coefficient f with crop row-water flow angle was $f_{15°} > f_{30°} > f_{45°} > f_{90°}$. This suggests that flow resistance of farmland vegetation is anisotropic. The water flow resistance coefficient of crops that were partly submerged increased with water depth, but decreased with water depth when the crop was completely submerged. At the critical change from partial submergence to complete submergence, the water flow resistance coefficient was the highest when water depth was equal to crop height. These results may be useful for optimizing farmland planting and soil and water conservation.

Keywords: hydraulic erosion; resistance coefficient; simulation experiment; vegetation resistance

The desertification of farmland, which is mainly caused by low or unpredictable precipitation, threatens global agricultural production and food security. Reasonable crop planting helps manage water and soil losses and is an effective method for reducing desertification. The slope flow of precipitation can be intercepted by crop stems and leaves which reduce flow speed. Thus the erosion of soil surface by slope flow can be decreased while soil water infiltration is enhanced. As such, reasonable crop planting can prevent hydraulic erosion, conserve water, reduce the risk of desertification, and help regulate the regional hydrological environment.

Farmland vegetation can provide significant protection against hydraulic erosion, i.e. the process of soil structure collapse and loss of nutrients finally leading to desertification. Konečná *et al*. (2014) found that the efficiency of narrow-row crop was 50–80% compared to bare soil. Zhang *et al*. (2014) demonstrated that farmland provided direct sediment interception and regulation mediated by the surface crop canopy, reducing runoff. Unlike under forest conditions, the effects of shoots and roots on soil loss were almost equivalent under farmland conditions. Kateb *et al*. (2013) showed that forested land had less precipitation runoff and soil loss than farmlands. Mathieu and Joannon (2013) suggested that crops are efficient at reducing soil erosion. Park *et al*. (2014) examined soil microbial responses to erosion-induced changes in the quantity and quality of organic matter in mountain grasslands.

The water flow resistance induced by vegetation is a mechanical index to measure the ability of vegetation resistance to hydraulic erosion which causes soil desertification. The more water flow resistance the farmland vegetation has, the greater the soil conservation capacity against hydraulic erosion. Water flow resistance can be measured using the

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Manning's roughness coefficient, Darcy-Weisbach resistance coefficient, and Chezy factor. Kim *et al.* (2012) studied the Manning's roughness coefficient of overland flow on surfaces with partially submerged plant, and they discovered that when plant cover fractions increase, the Manning's resistance coefficient also increases. Roche *et al.* (2007) found that the roughness coefficient increased with the submerged depth of crop; water flow is generally laminar under such condition and watershed loss is mainly caused by inertial forces. Konings *et al.* (2012) constructed a double layer velocity model to study the Manning's roughness coefficient with submerged crops. Västilä *et al.* (2013) used flume simulation to study the relationship between water flow resistance on submerged plants and plant leaf area and projection area of leaves along the projection direction. Aberle and Järvelä (2013) studied the impact of rigid and flexible floodplain plant on flow resistance.

Water flow resistance can be affected by the distribution of plants. Nehal *et al.* (2005) suggested that overall flow resistance is significantly influenced by the pattern of distribution of the plants. Luhar *et al.* (2008) showed that plant impacts water flow and transport and flow feedbacks influence plant spatial structure. Ye *et al.* (2015) found that plant distribution patterns impact the effects of overland flow resistance. Tang *et al.* (2014) suggested that plant friction may be related to other factors, such as the planting pattern.

Farmland cultivation differs from natural vegetation. It is characterized by more uniform planting, crop species, and height. Whether these features provide variable flow resistance and protection of surface soil loss remains unclear. But understanding the flow resistance response to farmland vegetation properties change is very important for farmland soil and water conservation to reduce desertification. Studies suggest that different plowing directions in fields affect surface runoff. For example, Hyväluoma *et al.* (2013) showed 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 unable to describe the effects of tillage-induced roughness. They introduced a flow-routing algorithm which accounts for the anisotropic roughness resulting from tillage (Hyväluoma *et al.* 2013). Sepaskhah and Shaabani (2007) found that hydraulic and geometric parameters were different for anguiform furrow irrigation compared with straight furrow irrigation. Manning's roughness coefficient in an anguiform furrow with real flow path was lower than that in straight furrow irrigation. Takken and Govers (2001) suggested that changes in runoff from a farmland slope could be caused by a change in tillage direction. The effect of crop planting direction, similar to the farmland farming direction, on flow resistance has not been previously reported. So flow resistance characteristics of farmland vegetation need investigation and study.

For the purpose of soil conservation to fight against desertification, farmland with identical crop planting directions and crop height and partial to complete submersion by water flow was simulated in this study to investigate the effect of crop on surface runoff. We examined the flow resistance, as well as the variation law and characteristics of water flow resistance of farmland vegetation with unique, consistent height.

MATERIAL AND METHODS

An open rectangular flume was constructed for the simulation experiment. The flume was 5 m long, 0.4 m wide, and 0.3 m high. The flume was divided into an upstream water level section, a 3 m long test section, and a downstream section. The test system consisted of a water tank, a rectangular tank, and a pressure gauge. A flow control valve was connected between the water flume and the water tank. Observation cross-sections were set within the experiment range. A glass plate was installed into the bottom of the tank. The artificial plants were 3 mm in diameter. Plant heights may vary significantly during different growth stages so the plant height when partly submerged was set at 15 cm and the height was 5 cm when plants were completely submerged. Artificial turf was installed at the bottom of water tank. In order to make the mapping relation between the field crop distribution and the laboratory hydraulic model relatively simple, the plant spacing of the hydraulic model was selected as 60 × 60 mm. The planting direction of rows and columns of plants formed specific angles in relation to the axis of the flume. Four angles (θ) between crop rows and water flow (15°, 30°, 45°, and 90°) were established for the simulation experiment to study the impact of planting direction on flow resistance. The sink bottom slope (i) was fixed as 1%. A total of 10–14 repeated experiments were conducted for each angle. The experimental apparatus and the position of the turf are shown in Figures 1 and 2.

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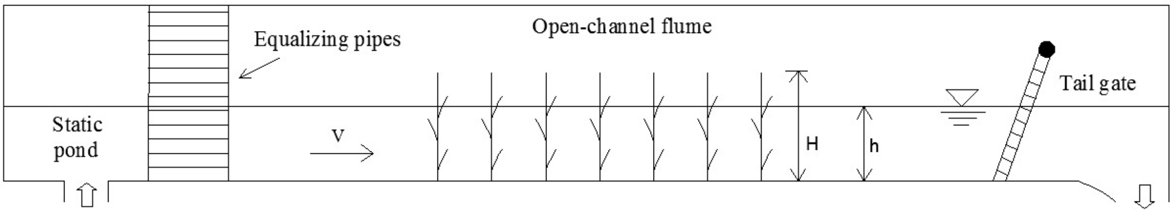

Figure 1. Diagram of the experimental flume

Farmland crops resist water flow runoff and protect the soil from erosion. Three parameters have been proposed to evaluate crop water flow resistance: Manning's roughness coefficient *n*, the Chezy factor *C*, and the Darcy-Weisbach resistance coefficient *f*. The relative advantages and disadvantages of the three methods of measuring water flow resistance have been considered by several researchers. Abrahams *et al.* (1994) found Darcy-Weisbach coefficient better than the Manning's coefficient because it can be applied to different flow states. Noarayanan *et al.* (2012) tested Manning's roughness coefficient under different water flow conditions and plant parameters and concluded that Manning's roughness coefficient is ideal for calculating and describing surface shallow flow resistance. Di Cristo *et al.* (2012) decided that only the Darcy-Weisbach resistance coefficient *f* can be applied to laminar flow and turbulent flow. Kadlec (1990) pointed out that the overland liquid flow through crop is usually transitional between laminar and turbulent flows, and is inappropriate for study using the Manning equation. Despite these differing opinions, there is agreement that the Darcy-Weisbach resistance coefficient *f* can be used for both laminar and turbulent flow, while the Manning's roughness coefficient *n* and the Chezy factor *C* are best used for turbulent flow. Considering that the tested flow may be an unstable transitional state between laminar and turbulent flow, the evaluation may be complicated using Manning's roughness coefficient *n* or the Chezy factor *C*, therefore the Darcy-Weisbach resistance coefficient *f* may be the best choice. Calculation of the Darcy-Weisbach resistance coefficient is as follows:

$$h_f = (H_1 - H_2) + \left(\frac{V_1^2}{2g} - \frac{V_2^2}{2g}\right) \quad (1)$$

$$f = h_f \frac{4\bar{R}}{l} \times \frac{2g}{\bar{V}^2} \quad (2)$$

where:
- H_1, H_2 – readings of the Manometry Tubes testing cross-section pressure (cm)
- V_1, V_2 – flow rates of cross section 1 and 2 (m/s)
- $\bar{R}$ – mean hydraulic radiuses (m)
- $\bar{V}$ – average flow velocity (m/s)
- h_f – water head loss from cross-section 1 to cross-section 2 due to friction (m)
- g – gravitation acceleration (m/s^2)
- l – length from cross-section 1 to cross-section 2 (1.5 m in this experiment)

Observation and calculation data are listed in Tables 1 and 2. Q is the electromagnetic flowmeter reading in m^3/h; h_1 and h_2 are water depth of cross-sections 1 and 2. The value is the difference between the reading of Manometry Tubes and the height of slope bottom. When the slope bottom is 1.0%, the heights of cross-sections 1 and 2 are 58.77 cm and 57.28 cm, respectively. h is the submerged height, and the value is the average of h_1 and h_2.

RESULTS AND DISCUSSION

Water resistance when crop is partially submerged. When the crop was partially submerged, the h~f relationship changed with the crop row-water flow angle (θ) (Figure 3). When the crop was partially

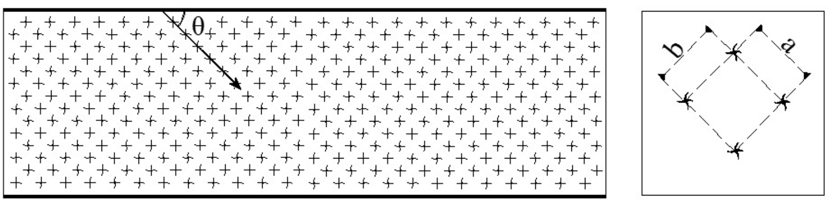

Figure 2. Sketch of flume bottom in the experimental section with 60 × 60 mm planting distributions, where θ is the angle of flow direction in relation to the direction of planting rows within the *a* × *b* planting distribution

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Table 1. Experimental observations and calculations for partially submerged plants

Manometry water level (cm)		Flow volume	Submerged height	Head loss	Resistance coefficient
H_1	H_2	(Q, m^3/h)	(h, m)	(h_f, m)	(f)
θ = 15°					
59.19	57.91	1.34	0.00525	0.014185	0.111700
59.50	58.22	2.56	0.00835	0.013998	0.125560
59.92	58.89	4.82	0.01380	0.012414	0.134535
60.11	59.19	5.80	0.01625	0.011541	0.138323
60.49	59.80	7.76	0.02120	0.009573	0.137741
60.61	60.00	8.51	0.02280	0.008952	0.131776
60.88	60.25	9.52	0.02540	0.008781	0.143641
61.15	60.55	10.68	0.02825	0.008331	0.148230
61.60	61.00	12.44	0.03275	0.008004	0.162552
62.51	61.95	16.42	0.04205	0.007300	0.175665
63.35	62.72	20.09	0.05010	0.007679	0.204007
64.38	63.71	24.90	0.06020	0.007857	0.228060
65.41	64.71	30.15	0.07035	0.008022	0.244586
66.98	66.19	38.33	0.08560	0.008709	0.281206
θ = 30°					
59.68	58.32	3.61	0.00975	0.014508	0.105661
59.93	58.65	4.83	0.01265	0.014006	0.122301
60.25	59.23	6.77	0.01715	0.012383	0.130796
60.40	59.48	7.45	0.01915	0.011520	0.137496
60.58	59.74	8.43	0.02135	0.010848	0.138529
60.76	60.00	9.51	0.02355	0.010210	0.135965
61.32	60.69	12.36	0.02980	0.008848	0.138290
62.00	61.35	15.01	0.03650	0.008468	0.162748
63.00	62.43	19.59	0.04690	0.007417	0.171435
64.30	63.60	25.58	0.05925	0.008234	0.216779
65.24	64.50	30.24	0.06845	0.008459	0.237921
66.20	65.45	35.82	0.07800	0.008489	0.243557
66.54	65.80	37.98	0.08145	0.008390	0.240866
θ = 45°					
59.58	58.17	3.76	0.00850	0.015009	0.067593
59.80	58.46	4.64	0.01105	0.014589	0.093015
59.94	58.79	5.72	0.01340	0.013847	0.100156
60.10	59.09	6.89	0.01570	0.013138	0.102492
60.22	59.32	7.53	0.01745	0.012286	0.107980
60.41	59.58	8.58	0.01970	0.011613	0.112064
60.61	59.88	9.65	0.02220	0.010678	0.115017
60.82	60.20	10.80	0.02485	0.009663	0.114814
61.12	60.61	12.62	0.02840	0.008664	0.110902
61.90	61.39	15.71	0.03620	0.007704	0.130637
62.60	62.08	18.96	0.04315	0.007392	0.143255
64.09	63.60	25.79	0.05820	0.006585	0.161265
65.90	65.24	35.25	0.07545	0.007789	0.210495
66.32	65.70	37.85	0.07985	0.007412	0.202689
θ = 90°					
59.73	58.15	4.42	0.00915	0.014663	0.059207
59.79	58.33	5.09	0.01035	0.014945	0.065962
59.95	58.56	6.23	0.01230	0.014930	0.072836
60.12	58.8	7.15	0.01435	0.014659	0.084986
60.25	59.15	8.38	0.01675	0.013945	0.090795
60.43	59.31	9.20	0.01845	0.013706	0.098744
60.80	60.21	12.46	0.02480	0.010717	0.094698
61.41	61.00	15.74	0.03180	0.008441	0.096304
62.24	61.88	19.15	0.04035	0.006831	0.105742
63.42	62.91	24.63	0.05140	0.007293	0.138055
64.59	63.96	30.17	0.06250	0.007893	0.173014
65.7	65.04	36.26	0.07345	0.007964	0.188900
66.14	65.43	38.77	0.07760	0.008341	0.201320

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Table 2. Experimental observations and calculations for completely submerged plants

Manometry water level (cm)		Flow volume	Submerged height	Head loss	Resistance coefficient
H_1	H_2	(Q, m^3/h)	(h, m)	(h_f, m)	(f)
θ = 15°					
63.40	62.81	23.15	0.05080	0.00774	0.160825
63.60	63.05	24.42	0.05300	0.007383	0.155195
63.77	63.31	25.84	0.05515	0.006654	0.139297
63.93	63.49	26.83	0.05685	0.006459	0.136571
64.10	63.65	27.73	0.05850	0.006498	0.139394
64.21	63.80	28.57	0.05980	0.006162	0.132336
64.32	63.91	29.42	0.06090	0.006169	0.131468
64.51	64.12	30.54	0.06290	0.005961	0.128921
64.72	64.33	31.92	0.06500	0.005938	0.128844
64.80	64.41	32.28	0.06580	0.005908	0.129702
64.91	64.51	33.23	0.06685	0.006009	0.130148
65.12	64.78	34.44	0.06925	0.005449	0.120982
65.29	64.95	35.57	0.07095	0.005431	0.12091
65.60	65.31	37.54	0.07430	0.004956	0.112341
θ = 30°					
63.40	62.80	23.89	0.05075	0.007942	0.154634
63.68	63.16	25.76	0.05395	0.007251	0.143862
63.80	63.29	26.42	0.05520	0.007133	0.143538
63.97	63.49	27.33	0.05705	0.006832	0.140747
64.10	63.60	28.34	0.05825	0.007008	0.142524
64.31	63.88	29.66	0.06070	0.006383	0.132702
64.40	63.98	30.18	0.06165	0.006278	0.131608
64.60	64.19	31.28	0.06370	0.006141	0.131287
64.79	64.38	32.51	0.06560	0.006117	0.131357
64.90	64.53	33.60	0.06690	0.005807	0.123196
65.00	64.61	34.13	0.06780	0.005950	0.126991
65.20	64.82	35.44	0.06985	0.005839	0.125489
65.39	65.00	36.31	0.07170	0.005859	0.129020
65.50	65.20	37.31	0.07325	0.005101	0.112627
θ = 45°					
63.70	63.30	26.23	0.05475	0.006294	0.124995
63.92	63.51	27.37	0.05690	0.006301	0.128189
64.11	63.79	28.74	0.05925	0.005531	0.114026
64.24	63.88	29.37	0.06035	0.005821	0.121149
64.55	64.20	30.86	0.06350	0.005621	0.122119
64.90	64.60	32.57	0.06725	0.005075	0.116000
65.04	64.74	34.53	0.06865	0.005190	0.111799
65.21	64.91	35.87	0.07035	0.005196	0.110947
65.40	65.10	36.94	0.07225	0.005147	0.111612
65.50	65.21	37.57	0.07330	0.005045	0.109997
θ = 90°					
63.79	63.41	25.92	0.05575	0.00596	0.127526
63.90	63.51	26.72	0.05680	0.006049	0.12842
64.11	63.78	27.87	0.05920	0.005479	0.119822
64.22	63.89	28.38	0.06030	0.005437	0.120748
64.52	64.20	30.58	0.06335	0.005355	0.117582
64.70	64.41	31.59	0.06530	0.005053	0.113057
64.82	64.51	32.50	0.06640	0.005229	0.115887
65.00	64.71	35.50	0.06830	0.005273	0.105864
65.18	64.89	34.56	0.07010	0.004978	0.113371
65.32	65.01	35.64	0.07140	0.005154	0.11622
65.49	65.21	36.72	0.07325	0.004871	0.110937
65.65	65.40	37.94	0.07500	0.004611	0.104921

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submerged, the crop resistance coefficient f in all directions increased with water depth, consistently with the results of ROCHE *et al.* (2007) and LI *et al.* (2013). These results were also similar to JARVELA's (2002) findings of the h~f relationship for rigid unsubmerged plants in open-channel flow, where f increased with h. This relationship may be related to the increasing total area of submerged crop stems and leaves meaning that the solid boundary surface between flow and crop (friction area) also increased. Frictional resistance under corresponding conditions also increased. Before the crop was completely submerged by the water flow, the resistance coefficient continued to increase with water depth.

Although both the depth and resistance coefficients showed monotonously increasing trends with different θ, different θ correspond to different resistance coefficients f at equal water depths, which can be summarized as $f_{15°} > f_{30°} > f_{45°} > f_{90°}$. Different θ indicate the different directions that water flow crosses through the crop. Experiments confirmed that different resistance occurs when water flows through crop at different directions. This indicates that the planting direction of crop affects the flow resistance of the submerged crop parts. The water flow resistance of crop is direction-sensitive and resistance changes with planting direction, suggesting that flow resistance of farmland is anisotropic.

Among the four angles tested, maximal and minimal resistances were detected at 15° and 90°, respectively. The plant spacing in the experiment was 60 × 60 mm. Therefore, when θ was 90°, water flowed through the farmland along the column of crop (we have defined the direction as the row in which the individual crop plants were placed). Therefore, the flow along rows or columns of the crop would meet minimum resistance, while the angle between the flow direction and the planting row or column would cause increasing resistance. We found that the projection area of the crop along the flow direction was the smallest at 90° when water flowed along the crop rows or columns. With the uniform arrangement of planting, the projection area of the adjacent row of the crop completely overlaps that of the previous row so that an increase in the row would not expand the projection area. The projection areas Ω at θ of 15°, 30°, and 45° can be described as $\Omega_{15°} > \Omega_{30°} > \Omega_{45°} > \Omega_{90°}$, and the corresponding resistance coefficient f was $f_{15°} > f_{30°} > f_{45°} > f_{90°}$. The projection area varied with planting direction and the resistance coefficient variation was consistent with projection area. However, details of the interaction between the two need further study.

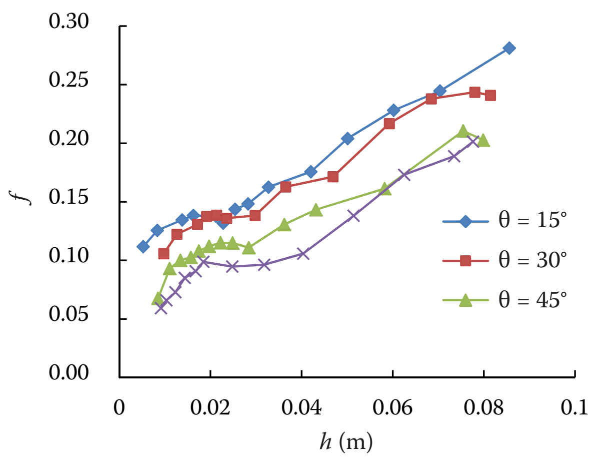

Figure 3. Relationship between runoff resistance coefficient f and water depth h for partially submerged plants

Effects of submersion on farmland water resistance. The impact of full submersion of vegetation was found to differ from that of partial submersion. LI *et al.* (2013) studied the Manning's vegetation roughness coefficient of submerged vegetation. VELASCO *et al.* (2003) explored the characterization of flow resistance due to flexible roughness of vegetation for different densities of submerged plants. FATHI-MOGHADAM *et al.* (2011) estimated the submerged vegetation roughness of flood plains with physical and numerical models. VERSCHOREN *et al.* (2016) developed a practical approach to quantify the resistance of submerged vegetation. It can be applied in 2D depth-averaged hydrodynamic models typically used in research. These studies focused on naturally submerged vegetation. Farmland vegetation differs from natural vegetation, characterized by more uniform planting, crops species, and height.

When the crop was completely submerged, the h~f relationship varied as θ changed (Figure 4). The crop resistance coefficient f in all directions decreased with increasing water depth. This relationship probably occurs because in fully submerged crops, the total surface area caused the friction force between crop and water to remain unchanged with increasing water depth, while the proportion of the bottom water in contact with crop was related to the gradual decrease in total flow. The friction caused by submerged crop was continuously homogenized with increasing cross-section area of the flow, which causes the resistance coefficient of the farmland to the whole water flow to decrease with increasing water depth.

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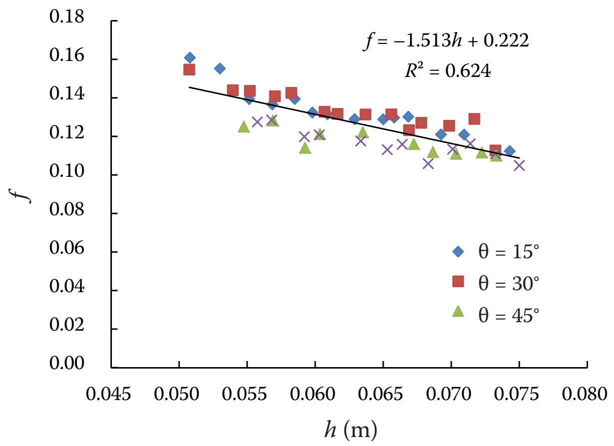

Figure 4. Relationship between runoff resistance coefficient f and water depth h for completely submerged plants

The h~f relationship values with different crop planting directions showed a bell-like distribution. The impact of planting direction on the h~f relationship was smaller when the crop was completely submerged by flow than when it was partially submerged. This was reflected in the smaller differences observed with varying angles. A significant difference among the resistance coefficients occurred between angles 90°/45° and 15°/30°, which can be described by $f_{15°} > f_{30°} > f_{45°} > f_{90°}$. When crop is completely submerged, θ affects flow resistance, but the effect is lower than when crop is partially submerged. This occurs because the impact of crop on the whole flow resistance decreases with increasing water depth weakening the difference caused by crop planting direction.

Because the impact of crop planting direction on flow resistance is minimal, we summarized all data with different θ into an overall sample ignoring the difference of planting direction for regression analysis. Results showed that when crops were completely submerged, the resistance coefficient f linearly decreased with water depth h.

Resistance coefficient related to the degree of crop submersion. The resistance coefficient of partially submerged crops gradually increased with increasing water depth but decreased when the crop was completely submerged. This suggests that resistance f should be the highest at the transitional state from partial to complete submersion. To test this, the water depth was increased to completely submerge the crop with θ set at 15° and 30°and monitored during the transition from partial to complete submersion. The relationship between water depth h and the resistance coefficient f is shown in Figure 5. The flow resistance coefficient peaked at a 5 cm water depth corresponding to the height just deep enough to submerge crop. The contact area between crop and water became the largest as did the resistance coefficient. A further increase of water depth decreased the proportion of water flow that provided friction with crop resulting in a decreasing resistance coefficient f.

Discussion on farmland vegetation water resistance. The water flow resistance of farmland vegetation is the ability of the crop to resist the action of hydraulic erosion and prevent soil loss. The vegetation induced resistance coefficient depends on the properties of vegetation (Busari & Li 2016; Zhang *et al.* 2016). The experimental results of farmland vegetation water resistance are of great value to improving the soil and water conservation of farmland. Under the partial submerged conditions, the water resistance of farmland vegetation increased with increases in the depth of the water. It shows a very

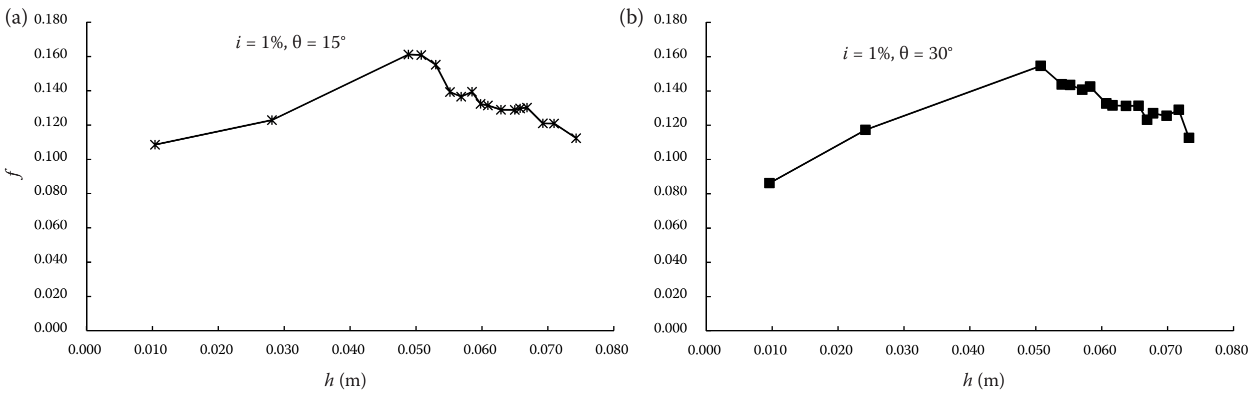

Figure 5. Relationship between runoff resistance coefficient f and water depth h when plants transit from partially submerged to completely submerged; plant row–water flow angle θ = 15° (a), θ = 30° (b); i = sink bottom slope

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good agreement with the study result of Jarvela (2002). In the case of completely submerged vegetation, the water resistance was found to decrease as water depth increased. These results can be applied to the selection of crop species to be planted for the purpose of soil and water conservation.

The experimental results show that the high stem crops can keep the partial submerged condition in a wide water depth change range, and therefore show a considerable water resistance. Once the crop is submerged, water resistance decreases. This indicated that the submersion method of irrigation reduced the degree of soil and water conservation, easily leading to the loss of farmland soil and water due to the total submersion of the crop.

The anisotropic characteristics of farmland vegetation hydraulics may help optimize the direction of crop planting to maximize soil and water conservation. However, it must be pointed out that these results were achieved using a simulation under laboratory conditions. Natural conditions would be affected by the degree and direction of the slope of the land and by hydrological factors such as rainfall and surface soil moisture (Ishikawa *et al.* 2000; Stone & Shen 2002; Nepf *et al.* 2007; Kubrak *et al.* 2008). The results obtained by the experiments, when applied to more complex natural conditions, may affect the applicability of the results under natural conditions.

CONCLUSION

Farmland was studied in situations with identical planting direction, unique crop type, and similar crop height. It was determined how these variables influence protection against hydraulic erosion using a hydraulic model to simulate conditions in which the crop is partially or completely submerged by water flow and by the analysis of the transitional condition between emerged and totally submerged. The following may be concluded here: (1) The direction of planting influences water flow on the slope, and the resistance of crop varies with changing angle between the water flow and the planting direction. This indicates that flow resistance of farmland is anisotropic. This effect is greater when the crop is partially submerged, and the resistance coefficients at tested angles were (greatest to least) $f_{15°} > f_{30°} > f_{45°} > f_{90°}$. This relationship is valuable for optimizing the use of farmland planting to minimize surface runoff and reduce soil erosion. (2) Farmland with different planting directions can have significantly different flow resistance coefficients when partially submerged. The projection area to the direction of flow varies with different direction of planting. The change of projected area is consistent with the change of resistance coefficient, but the specific interaction between the two is unknown. (3) Flow resistance increases with water depth when the crop is partially submerged but decreases after the crop is completely submerged. (4) Because the height of farmland vegetation is comparable to natural vegetation, a water depth that completely submerges the crop represents the critical condition corresponding to the highest water resistance coefficient.

These results achieved using simulation under lab conditions may be useful for optimizing farmland planting and soil and water conservation. The field conditions are rendered more complex because of the effect of many factors. The effects of these factors on resistance will require further studies.

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