Rigid vegetation affects slope flow velocity

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Abstract

The mean slope flow velocity is critical in soil erosion models but the mechanism of its variation under rigid vegetation cover remains unclear. On natural slopes, vegetation grows predominantly perpendicular to the horizontal plane (BH), with some growing perpendicularly to the slope surface (BS); however, current research often neglects the effects of these two growth directions on the mean flow velocity. We conducted simulation experiments using different coverage levels, rigid vegetation, slope angles, and flow rates and showed that the flow rate and slope significantly influenced the mean flow velocity. As the coverage of rigid vegetation increased, the mean flow velocity increased more under conditions perpendicular to the horizontal plane (BH) and those perpendicular to the slope (BS). A model for predicting mean flow velocity was developed using vegetation equivalent roughness and the Manning formula, which accurately predicted flow velocity in different conditions. This study contributes to the refinement of slope flow theory and provides data that supports soil and water conservation efforts.

Introduction

Soil erosion is a serious ecological and environmental problem that concerns many researchers worldwide\[1–3\]. The basic unit of hydraulic erosion is slope runoff, for which the hydraulic properties are intimately linked to soil erosion. Thus, understanding these hydraulic characteristics is essential for studying the soil erosion process. Flow velocity is a fundamental and primary factor in the hydraulic properties of slope runoff and is used in the computation of additional hydraulic factors, including shear force and stream power, which are important parameters for analyzing soil detachment and sediment transport processes\[4, 5\]. Studying flow velocity from slope runoff not only sheds light on erosion origins but also lays the foundation for creating predictive models of soil erosion \[6\].

The Loess Plateau in Northwestern China is characterized by loose soil\[7\] and significant precipitation variability\[8\]. In this region, severe degradation of unsustainable land over time and the fragile ecological environment make it some of the worst soil erosion worldwide. To mitigate the damage caused by soil erosion, the Chinese government implemented the Grain for Green policy in 2000\[9\]. Vegetation prevents soil erosion and slows desertification through sediment interception and litter accumulation\[10, 11\]. The properties of the underlying slope surface are one of the many factors that affect the flow velocity of slope runoff\[12, 13\], making its mechanism complex. Thus, research is required to determine how vegetation affects slope runoff flow velocity. Liu et al.\[14\] conducted experiments on 30 slopes with varying degrees of vegetation coverage, including a complete mix of grass and shrubs, which showed that slopes with vegetation cover had a noticeably higher resistance coefficient than that of slopes without vegetation cover, indicating that vegetation reduced the slope flow velocity. Li and Pan\[15\] also found that vegetation significantly increased the resistance coefficient of slopes and decreased flow velocity, while Zhang and Hu\[16\] found that removing the aboveground components of vegetation significantly increased the slope flow velocity. These findings indicate that the aboveground components of vegetation are more effective in reducing flow velocity and increasing hydraulic roughness than the belowground parts. Conversely, vegetation has also been reported to increase slope flow velocity. For
example, Cen et al. [17] observed that the average flow velocity initially rose with an increase in vegetation amount before eventually declining. Vegetation alters surface roughness and affects the water flow [18]; the larger the rough elements, the more concentrated the surface runoff [19], which can also increase the flow velocity. Given the complex relationship between vegetation cover and flow velocity and contradicting results in the literature, it is necessary to further study this relationship to refine the theory of slope flow.

Vegetation characteristics such as shape, stiffness, degree of submergence, and arrangement, influence the hydrodynamic properties of slope flow [20]. Cen et al. [21] studied the hydrodynamic properties of slope flow under combinations of flexible and rigid vegetation and found that different types of vegetation can differentially affect flow resistance. Serio et al. [20] also studied the hydraulic characteristics of flowing rivers under the influence of rigid and flexible vegetation and found that the density and rigidity of vegetation affected the spatiotemporal distribution of the average flow velocity to different degrees. Wu et al. [22] found that the water depth increased with the diameter of the rigid vegetation, and the flow velocity behind the vegetation was lower than that inside its gaps. Teng et al. [23] reported that the distribution of flow velocity under different arrangements of rigid vegetation was lower close to the channel bottom and in the inner layers of the vegetation, with flow velocities along the water depth displaying S-shaped and inverse S-shaped profiles. Most simulation studies on vegetation set the growth direction of vegetation perpendicular to the slope (BS) [21, 24, 25]; however, in nature, vegetation can also grow perpendicular to the horizontal plane (BH). As there is little research that focuses on the effects of vegetation growth direction on average flow velocity, the impacts of these two types of vegetation on slope flow velocity must be measured independently.

The prediction of the mean velocity has been a focal point of research [26] and it is essential to estimate the mean velocity accurately to forecast runoff and sediment output [12]. Nearing et al. [27] hypothesized that the mean velocity could be represented by a power function of the discharge, while other scholars argue that the prediction of the mean velocity should consider coverage in situations with a cover [28]. Additionally, the Manning formula is widely used to predict the slope flow velocity because it includes the water depth and roughness in its estimation of flow velocity [29]. However, this formula assumes many constraints such as uniform flow and, therefore, additional factors must be considered when modifying the formula for practical applications. For example, Cen et al. [17] combined the principle of equal roughness adjustment with the Manning formula to establish a flow velocity prediction model, while Fu et al. [30] reported that the Manning formula did not accurately predict the mean velocity under certain vegetation coverage. Overall, further research is needed to develop formulae that predicts the mean velocity of slope flow under vegetation.

In conclusion, it is unclear how slope vegetation affects mean flow velocity and differences in vegetation types can vary patterns of flow velocity changes. It is also unclear whether the two growth directions of rigid vegetation have different effects on the velocity of the slope flow, further necessitating refinement of flow velocity prediction models and their applicability under conditions of rigid vegetation cover. The aims of this investigation were as follows: (1) to investigate the patterns of change in mean velocity
under different slope and flow conditions; (2) to analyze the impact of rigid vegetation and its growth direction on mean velocity; and (3) to develop a new mean velocity prediction model using the Manning equation and to compare the accuracy and applicability of different flow velocity prediction models. This study contributes to the refinement of slope flow theories and supports soil and water conservation efforts.

Materials and methods

Experimental design

The experimental plot consists of an acrylic tank with an adjustable slope, ranging from 0° to 30°, 3.8 m in length, 0.3 m in width, and 0.2 m in depth (Fig. 1). A grid-shaped flow stabilizer was installed at the inlet of the tank to maintain the stability of the inflow water. The water supply for the experiment was a rectangular tank equipped with a low-flow water pump (QDX100-8-3.5, SRCH, Shanghai, China). The experimental flow was regulated using a glass rotor flow meter (LZB-40, SKJYLEAN, Suzhou, China) designed for a range of 250–2500 L/h. To achieve a uniform roughness scale on the bed, the bottom of the tank was lined with 40-mesh water sandpaper with a 0.38 mm roughness ($k_{sb}$). Rigid vegetation, which is a common type of vegetation used in experiments, is typically simulated using cylinders\[31\]. In this experiment, rigid vegetation was simulated using 2 cm diameter PVC pipes, with the vegetation-covered section of the tank extending 2 m with a 20 cm section reserved at the front as a flow stabilization area (Fig. 2). The experiment included 95, 187, and 286 pieces of rigid vegetation, with coverage determined by dividing the area of the covered region by the cross-sectional area of each stem as follows:

$$C_r = \frac{N\pi D^2}{4BL}$$

Equation (1) calculates vegetation coverage perpendicular to the slope direction (BS), where $C_r$ is the vegetation coverage, $N$ is the number of rigid vegetation cells in the test area, $D$ is the diameter of the PVC pipe (0.02 m), $B$ is the width of the experimental flume (0.3 m), and $L$ is the length of the area covered by vegetation (2.0 m). For vegetation perpendicular to the horizontal plane (BH), coverage was calculated using the formula for the area of an ellipse (Eq. 2), where $\theta$ is the angle of the slope.

$$C_r = \frac{N\pi D^2}{4BL\cos\theta}$$

Equation (2)

Slopes $\theta$ were set at 5°, 10°, 15°, and 20°, which resulted in slope ratios $S$ of 0.0872, 0.1737, 0.2588, and 0.3420, respectively. The designed discharge rates were 5, 10, 20, 30, and 40 L·min$^{-1}$, which
corresponded to per-width flow rates of 0.000278, 0.000556, 0.001111, 0.001667, and 0.002222 m³·m⁻¹·s⁻¹, respectively, with five levels of treatment. Three longitudinal observation sections were set along the flume from top to bottom, at 0-0.75 m, 0.75–1.5 m, and 1.25-2.0 m, respectively. Water depth \( h \) was measured using a water level gauge (model: SCM60, The Leader, Shanghai, China; accuracy ± 0.01 mm). In each of the three sections, measurements were taken four times, totaling 12 measurements, which were averaged to obtain the final results. If the standard deviation of the results was > 5%, re-testing was necessary.

(a) Pipes were positioned perpendicular to the slope or (b) perpendicular to the horizontal plane of the slope.

**Hydrodynamic parameters**

The formula for calculating mean velocity \( u \) is as follows:

\[
u = \frac{Q}{h \times b_1}
\]

3

In the Eq. (3), \( Q \) is the design flow rate (m³·s⁻¹), \( h \) is the average water depth of the cross-section (m), and \( b_1 \) is the effective width of the water flow in the experiment (m).

Equation (4) defines \( b_1 \) as follows:

\[
b_1 = B \times (1 - C_r)
\]

4

Equation (5) was used for calculating the Reynolds number \( Re \) as follows:

\[
Re = \frac{uR}{\nu_0}
\]

5

where \( R \) is the hydraulic radius (m) and \( \nu_0 \) is the kinematic viscosity (m²·s⁻¹), which was calculated with Eq. (5) as follows:

\[
\nu_0 = \frac{0.01775}{1 + 0.0337t + 0.00022t^2}
\]

6

where \( t \) is the reading from the thermometer near the flow stabilizer (°C).
Equation (7) was used for calculating the Darcy–Weisbach resistance coefficient $f$ as follows:

$$f = \frac{8gRS}{u^2}$$

Equation (8) was used to calculate the hydraulic radius $R$:

$$R = \frac{A}{P}$$

where $A$ is the cross-sectional area ($m^2$) through which water passes and is calculated as follows:

$$A = b_1 \times h$$

$P$ is the wetted perimeter ($m$) and is calculated as follows:

$$P = \begin{cases} \frac{2HL + (BL - h)C_{th} D h N}{4} & \text{(10)} \\ \frac{2HL + (BL - h)C_{th} D h N}{4} & \text{(11)} \end{cases}$$

Equation (10) is the calculation formula for the wetted perimeter of vegetation oriented perpendicularly to the slope (BS) and Eq. (11) is for vegetation oriented perpendicularly to the horizontal plane (BH).

**Data Processing**

**Model accuracy assessment indicators**

In this study, the accuracy of the mean velocity prediction model was assessed using the adjusted coefficient of determination $\text{Adj.R}^2$, Nash-Sutcliffe efficiency coefficient $\text{NSE}$, and relative root mean square error $\text{RRMSE}$. The formulae for these three evaluation indicators were as follows:
\[ R^2 = \frac{\left[ \sum_{i=1}^{n} [O_i - \bar{O}] [P_i - \bar{P}] \right]^2}{\sum_{i=1}^{n} [O_i - \bar{O}]^2 \sum_{i=1}^{n} [P_i - \bar{P}]^2} \tag{12} \]

\[ adjR^2 = 1 - (1 - R^2) \frac{n}{n - p - 1} \tag{13} \]

\[ NSE = 1 - \frac{\sum_{i=1}^{n} [O_i - P_i]^2}{\sum_{i=1}^{n} [O_i - \bar{O}]^2} \tag{14} \]

\[ RRMS = \sqrt{\frac{1}{n} \sum_{i=1}^{n} [O_i - P_i]^2} \tag{15} \]

where, \( O_i \) is the observed value, \( \bar{O} \) is the mean of the observed values, \( P_i \) is the simulated value, \( \bar{P} \) is the mean of the simulated values, \( n \) is the number of samples, and \( p \) is the number of parameters.

### Statistical analysis

One-way analysis of variance (ANOVA) was conducted on the mean velocities under different flow rates, slopes, coverage levels, and types of coverage using the SPSS 26 software (IBM SPSS Statistics, Armonk, NY, USA), with a significance level of \( p < 0.05 \). The nonlinear regression fitting function in SPSS 26 was used to construct a mean velocity prediction model. R Studio and Origin 2023 were used to create graphics for visualization purposes.

### Results

#### The impact of flow rate and slope on mean velocity

As the flow rate increased, the distribution range of the mean velocity increased, with flow rates of 5, 10, 20, 30, and 40 \( \text{L} \cdot \text{min}^{-1} \) showing mean velocity distribution ranges of 0.117 to 0.245 m\( \cdot \)s\(^{-1} \), 0.140 to 0.314 m\( \cdot \)s\(^{-1} \), 0.178 to 0.393 m\( \cdot \)s\(^{-1} \), 0.202 to 0.463 m\( \cdot \)s\(^{-1} \), and 0.213 to 0.582 m\( \cdot \)s\(^{-1} \) for BS; and 0.158 to 0.307 m\( \cdot \)s\(^{-1} \), 0.183 to 0.419 m\( \cdot \)s\(^{-1} \), 0.204 to 0.482 m\( \cdot \)s\(^{-1} \), 0.222 to 0.463 m\( \cdot \)s\(^{-1} \), and 0.238 to 0.582 m\( \cdot \)s\(^{-1} \) for BH, respectively (Fig. 3). These results indicated that the flow rate and slope significantly affected the mean velocity distribution range \( (p < 0.05) \). Comparison of the two vegetation conditions revealed that at lower flow rates \( (5, 10, 20 \text{ L} \cdot \text{min}^{-1}) \), the range of mean velocity under BS was smaller than those under BH. At higher flow rates \( (30 \text{ and } 40 \text{ L} \cdot \text{min}^{-1}) \), the mean velocity distribution range under BS conditions was similar to that under BH conditions. As the slope increased, the distribution range of the mean velocity also increased. At slopes of 5°, 10°, 15°, and 20°, the ranges were 0.117 to 0.475 m\( \cdot \)s\(^{-1} \), 0.179 to 0.498 m\( \cdot \)s\(^{-1} \), 0.167 to 0.557 m\( \cdot \)s\(^{-1} \), and 0.166 to 0.582 m\( \cdot \)s\(^{-1} \) for BS conditions; and 0.158 to 0.475 m\( \cdot \)s\(^{-1} \), 0.179 to 0.498 m\( \cdot \)s\(^{-1} \), 0.186 to 0.557 m\( \cdot \)s\(^{-1} \), and 0.166 to 0.582 m\( \cdot \)s\(^{-1} \) for BH conditions, respectively;
indicating that the range of the mean velocity distributions were similar under both BS and BH conditions.

The impact of rigid vegetation on mean velocity

Under rigid vegetation cover conditions, the mean velocity of the slope flow was influenced by a combination of vegetation coverage, flow rate, and slope. At low flow rates, the mean velocity initially increased and then decreased with changes in vegetative coverage (Fig. 4). For instance, at a slope of 5° and flow rate of 5 L·min$^{-1}$, the mean velocity increased 0.158, 0.177, 0.145, and 0.117 m·s$^{-1}$ with increasing coverage ($N = 0–286$) under BS conditions, while at a slope of 10° and flow rate of 10 L·min$^{-1}$, the mean velocity rates were 0.274, 0.312, 0.301, and 0.279 m·s$^{-1}$ with increasing coverage ($N = 0–286$) under BH conditions. At a slope of 5° and a flow rate of 30 L·min$^{-1}$, mean velocities with increasing BH coverage conditions were 0.403, 0.274, 0.245, and 0.222 m·s$^{-1}$, indicating that at lower slopes, as the flow rate increased, the mean velocity gradually decreased. At medium-to-high slopes (10–20°), the mean velocity gradually decreased and then increased as flow rate increased, and was most pronounced at a flow rate of 20 L·min$^{-1}$. Indeed, at a slope of 20° and a flow rate of 20 L·min$^{-1}$, mean velocities with increasing coverage were 0.393, 0.348, 0.288, and 0.358 m·s$^{-1}$ under BS conditions. At a flow rate of 5 L·min$^{-1}$ and slopes of 15° and 20°, the rate of change in the range of mean velocities is 54.9% and 85.3% respectively; indicating that as the flow rate increased, the differences in velocity between different coverage levels decreased, and the rate of velocity stabilizes. However, at a flow rate of 40 L·min$^{-1}$ and slopes of 15° and 20°, the rate of change in the range of mean velocities was only 23.9% and 20.9%, respectively; suggesting that the change trend of mean velocity at high discharge is more gentle than that at low discharge, and the influence of rigid vegetation on velocity at low discharge is more obvious.

Under different slope and flow conditions, the coverage and type of rigid vegetation significantly affected the mean velocity ($p < 0.05$). To compare the effects of the two types of rigid vegetation on the mean velocity, we used a velocity ratio defined as the velocity under BS conditions ($u_{BS}$) divided by that under BH conditions ($u_{BH}$). A velocity ratio greater than 1 indicated that the velocity under the BS conditions was greater than that under the BH conditions, and vice versa. Correlation tests revealed significant relationships among the velocity ratio and Reynolds number ratio, resistance coefficient ratio, and flow rate ($p < 0.05$), with Pearson correlation coefficients of 0.83, -0.95, and 0.61 respectively. As the Reynolds number ratio and flow rate increased, the velocity ratio increased (Fig. 5), whereas an increase in the resistance ratio led to a decreased velocity ratio. All together, these results indicated not only does the difference in rigid vegetation coverage affect the average flow velocity, but also the direction of rigid vegetation growth (BS and BH) affects the flow velocity.

Mean velocity prediction model

The prediction of mean velocity has been a major area of research among scholars[27, 32], with the mean velocity expressed as a power function of slope and flow rate, with vegetation coverage being a
determinant of exponential size[33]. Nonlinear regression analysis was performed on the experimental data, and the results are presented in Table 1.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Fitting formula</th>
<th>Adj.(R^2)</th>
<th>NSE</th>
<th>RRMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS</td>
<td>(u = 16.050Q^{0.424}S^{0.320})</td>
<td>0.83</td>
<td>0.83</td>
<td>0.15</td>
</tr>
<tr>
<td>BH</td>
<td>(u = 7.481Q^{0.319}S^{0.331})</td>
<td>0.77</td>
<td>0.77</td>
<td>0.15</td>
</tr>
<tr>
<td>ALL</td>
<td>(u = 9.328Q^{0.347}S^{0.356})</td>
<td>0.80</td>
<td>0.80</td>
<td>0.15</td>
</tr>
</tbody>
</table>

BS for perpendicular to the slope surface; BH for perpendicular to the horizontal plane; ALL for considering all data combined; Adj. \(R^2\): Adjusted R-squared;

NSE: Nash-Sutcliffe Efficiency; RRMSE: Relative root mean square error; \(u\) is mean velocity; \(S\) is slope ratios; \(Q\) is the design flow rate \((m^3s^{-1})\).

The relationship between the predicted and measured mean flow velocities were calculated using Eq. (18), which indicated that the adj. \(R^2\) under BH conditions was 0.77 (Eq. 17), while the adj. \(R^2\) for the prediction model fitted with all data was 0.80 (Eq. 18; Fig. 6c). Because of the more complex dynamics of overland flow compared to open-channel flow, especially when surface runoff is influenced by vegetation, using only flow and slope for prediction is not ideal[34]. For slopes covered with vegetation, proposed theories such as vegetation equivalent resistance coefficients[26] and vegetation-based roughness height[35] integrate the effects of vegetation on overland flow with the underlying surface impacts to enhance the practicality of hydraulic models. Rigid vegetation acts as a roughness element on slopes and its impact can be quantified using the resistance coefficient formulas for rough areas[35]:

\[
f = \left(2\log\frac{3.7h}{k_{sv}}\right)^{-2}
\]

Equations (19) and (7) calculate the resistance coefficients; thus, by combining and rearranging them, we can derive the vegetation-equivalent roughness height \(k_{sv}\) (mm):

\[
k_{sv} = \frac{3.7h}{10^{0.5\sqrt{\frac{u^2}{gHS}}}}
\]
Because the substrate used in this experiment was 40-mesh sandpaper, the roughness height of the slope outside the vegetated area remained constant ($k_{sb} = 0.38 \text{ mm}$). Adding the rigid vegetation equivalent roughness height $k_{sv}$ to that of the non-vegetated area $k_{sb}$ yielded the equivalent roughness height $k_{se}$ (mm) of the slope under stiff vegetation cover. The formula is as follows:

$$k_{se} = k_{sv} + \left(1 - Cr\right)k_{sb}$$

21

The equivalent roughness height $k_{se}$ of the slope under stiff vegetation was correlated with the slope, flow, and coverage. For easier field observation and application, a nonlinear fit using the equivalent roughness height $k_{se}$, flow rate $Q$, energy slope $S$, and coverage $Cr$ was performed using the following equations:

$$k_{se} = 132.154Q^{0.718}S^{-0.753}e^{6.984Cr}$$

22

The adj. $R^2$ value of Eq. (22) was 0.78, indicating that the model structure was reasonable. Manning's resistance coefficient $n$ depends on the vegetation coverage and soil type[36]. Because this experiment was a fixed-bed test, the Manning's coefficient was primarily influenced by the coverage of rigid vegetation. The formula used for calculating Manning's coefficient $n_v$ under vegetation cover is as follows:

$$n_v = \frac{1}{u}R^{m_1}S^{m_2}$$

23

where $m_1$ and $m_2$ are the exponents of hydraulic radius $R$ and energy slope $S$, respectively. Compared with the basic Manning formula, the use of the hydraulic radius $R$ was more appropriate because of the changes in water depth $h$ caused by rigid vegetation cover. Wu et al.[37] found that Manning's coefficient decreases with increasing water depth and increases with increasing slope roughness. This is similar to the findings of Yang et al.[38], who reported that Manning's coefficient $n_b$ for slopes without vegetation cover can be expressed as a function of the slope roughness height $k_{sb}$ and water depth $h$, using the specific function form:

$$n_b = \frac{k_{sb}^{m_3}}{h^{m_4}}$$

24

where $m_3$ and $m_4$ are the exponents of the slope roughness height $k_{sb}$ and water depth $h$, respectively. Similarly, by replacing the slope roughness height $k_{sb}$ in Eq. (24) with the equivalent roughness height $k_{se}$, we can obtain the following equation:

$$n = \frac{k_{se}^{m_3}}{h^{m_4}}$$

This equation can be used to calculate Manning's coefficient $n$ under vegetated conditions.
under a rigid vegetation cover, the formula for the equivalent vegetation Manning coefficient \( n_{ve} \) was derived as:

\[
n_{ve} = \frac{k_{se}^{m_3}}{h^{m_4}}
\]

By combining Equations (23), (24), and (25), the model expression for the mean flow velocity \( u \) was constructed:

\[
u = \frac{a_1 R^{a_2} S^{a_3} h^{a_4}}{k_{se}^{a_5}}
\]

where \( a_1, a_2, a_3, a_4, \) and \( a_5 \) are the constants. The equivalent roughness height \( k_{se} \) of the slope in Eq. (26) can be calculated using Eq. (22) and the flow velocity prediction model was obtained after nonlinear fitting of the experimental data (Table 2).

**Table 2**

The mean velocity prediction model using the equivalent roughness height \( k_{se} \)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Fitting formula</th>
<th>Adj.R(^2)</th>
<th>NSE</th>
<th>RRMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS</td>
<td>( u = \frac{1.975 R^{0.025} S^{0.741} h^{-5.892}}{k_{se}^{0.813}} ) 0.88</td>
<td>0.88</td>
<td>0.12</td>
<td>(27)</td>
</tr>
<tr>
<td>BH</td>
<td>( u = \frac{1.705 R^{0.050} S^{0.683} h^{-4.940}}{k_{se}^{0.677}} ) 0.88</td>
<td>0.88</td>
<td>0.12</td>
<td>(28)</td>
</tr>
<tr>
<td>ALL</td>
<td>( u = \frac{1.369 R^{0.300} S^{0.731} h^{-5.222}}{k_{se}^{0.774}} ) 0.87</td>
<td>0.86</td>
<td>0.12</td>
<td>(29)</td>
</tr>
</tbody>
</table>

BS for perpendicular to the slope surface; BH for perpendicular to the horizontal plane; ALL for considering all data combined; Adj. \( R^2 \): Adjusted R-squared;

NSE: Nash-Sutcliffe Efficiency; RRMSE: Relative root mean square error; \( u \) is mean velocity; \( S \) is slope ratios; \( R \) is the hydraulic radius (m); \( h \) is the average water depth (m); \( k_{se} \) is equivalent roughness height (mm).

**Discussion**

The impact of flow rate and slope on mean velocity
The mean flow velocity $u$, a crucial hydraulic characteristic in soil erosion modeling, is influenced by the flow rate[39], slope, and surface conditions. In this experiment, slope and flow rate increased the mean flow velocity, which suggested that the gravitational potential energy of the water flow rises as the slope becomes steeper, resulting in higher flow velocities on the slope. This outcome aligned with the findings of Zhang et al.[40] and Liu et al.[28]. Whether on a smooth bare slope or a slope with surface cover, $u$ exhibits a strong correlation with both the slope and the flow rate [6]. For instance, Liu et al.[41] found that on gravel-covered slopes, the correlation coefficients between the mean flow velocity, flow rate, and slope were 0.716 and 0.674, respectively. Similarly, the slope factor and rate of straw addition could be used to estimate $u$ on slopes with added straw ($R^2 = 0.91$)[42]. However, Ali et al.[43] found that under mobile bed conditions, the slope did not significantly affect $u$, which may be due to the different substrate conditions. In our study, the substrate and bed conditions were kept constant throughout the experiment, to explore how the flow rate and slope affected the morphology and roughness of erosive slopes. Giménez et al.[44] suggested that slope roughness is positively correlated with slope; thus, the greater the slope, the rougher the slope surface. A rougher substrate can offset the kinetic energy converted from the gravitational potential energy[45], thus resulting in no significant change in $u$.

**The impact of rigid vegetation on mean velocity**

It is commonly believed that vegetation increases surface roughness and that the energy of the slope flow is mainly consumed by the surface roughness caused by the aboveground parts of vegetation[46]. Thus, vegetation reduces the mean flow velocity $u$ on slopes. For example, under three different vegetation covers, the flow velocity on slopes decreased by 28%-30% [15]. Liu et al. [47] added different amounts of straw to slopes to increase surface roughness and found that flow velocities decreased by 28.44%, 44.09%, and 55.56%. However, in our experiment, there was no monotonic decrease in the association between $u$ and the coverage of rigid vegetation, and $u$ was differentially influenced by the test conditions (Fig. 4). At low flow rates, with the increase of slope, $u$ changes from first increasing and then decreasing to increasing. At high flow rates, $u$ first decreased and then increased in response to increasing vegetative coverage conditions. The primary reason for the increase in $u$ was that the rigid vegetation changed the cross-sectional area of the flow on the slope, which impacted the spatial distribution of the water [15]. Rigid vegetation was the primary roughness element on the slope and reduced flow velocity due to its obstructive effect, while also accelerated water flow through non-vegetated areas, forming concentrated flows and increased velocity[48]. Our findings are supported by that of Wu et al.[22], who observed that the flow velocity behind rigid vegetation was lower than that within vegetation gaps using a three-dimensional laser doppler velocimeter. Vegetation also affects water depth by increasing the water level upstream and decreasing it downstream of vegetation[49]. This backwater-induced local pressure difference increases the local flow velocity and shear stress, increasing the erosion risk near the vegetated areas[50]. Zhao et al.[24] used PVC pipes to replicate rigid vegetation and showed that the flow velocity increases marginally with greater coverage. At low flow rates, the critical coverage for the increase in the mean flow velocity was low, and this critical coverage increased as the flow rate increased. The main resistance to flow on slopes comes from the particle resistance generated by the slope and the form resistance created by vegetation[51], with particle
resistance that generally decreases as the flow rate and slope increase[34]. At low flow rates, the slope flow is slower and shallower, and vegetation with low coverage compresses the water flow space, increasing the flow velocity. As the flow rate increased, both the flow velocity and water depth increased, at which time the particle resistance on the slope was gradually replaced by the form resistance of the vegetation. The increased flow velocity owing to the compression of the water cross-sectional area by vegetation at low coverage cannot replace the reduced flow velocity owing to vegetation form resistance[34]. Under these conditions, the compression of the water flow space by high coverage vegetation becomes more pronounced[52], leading to increased flow velocity.

For the two different types of rigid vegetation used in our study (BS and BH), the morphological differences resulted in different degrees of obstruction to the water flow, which affected the mean flow velocity. We found that under BS conditions, the average flow velocity (0.311 m·s$^{-1}$) was higher than that under BH conditions (0.331 m·s$^{-1}$). The velocity ratio had a positive correlation with both the flow ratio and the Reynolds number ratio, while it had a negative correlation with the resistance coefficient ratio. We found that most Reynolds number ratios and velocity ratios were generally less than 1 (Fig. 5), indicating that under BS conditions, the rigid vegetation significantly obstructed water flow, inhibited changes in the slope flow state, and lowered the flow velocity. Similarly, an increase in flow suggested greater water depth. Under the BS conditions, vegetation compressed the flow more significantly; therefore, under high-flow and BS conditions, the flow velocity gradually exceeded that reported under the BH conditions. These findings are in agreement with those of Schoelynck et al. [53], who postulated that vegetation on a slope provides less hindrance to water flow because it is more streamlined. Shan et al.[54] also found that the angle at which vegetation is deflected increases the water flow when the water flow contacts the vegetation perpendicularly (e.g., BS), it encounters greater obstruction, whereas when the vegetation is angled (e.g., BH), it exerts less drag, making it easier for the flow to bypass[55].

**Evaluation of the mean flow velocity prediction model**

Traditional hydraulic models consider flow velocity as a power function of both the flow rate and slope [28]. However, on vegetated slopes, flow rate and slope are no longer the sole factors affecting flow velocity[56]. Equations (16–18) reflect the mean flow velocity prediction models fitted using the slope and flow rate as variables. For all data, Eq. (18) has an adj.$R^2$ and $NSE$ of 0.80 each, with Fig. 6c showing data points near the 1:1 line, although some points are scattered. Compared to Eq. (18), Eq. (29) improved the adj.$R^2$ and $NSE$ to 0.87 and 0.86, respectively; and the $RRMSE$ decreases from 0.15 to 0.12. Additionally, Fig. 6d illustrates that the data points are evenly distributed along the 1:1 line, with less dispersion than that in Eq. (18). This demonstrates that utilizing the vegetation equivalent roughness height to predict $u$ is rational and yields a highly accurate model. Furthermore, it is unreasonable to predict $u$ solely based on the flow rate and slope on slopes with rigid vegetation; therefore, factors related to vegetation must be considered when predicting mean flow velocities.

To enhance the representativeness of our model results, we examined the flow velocity models from the literature [27, 17]. Nearing et al.[27] reported experiments that were conducted on soil slopes and the
results showed that the model's adj. $R^2$, NSE, and $RRMSE$ were 0.45, -0.01, and 0.34, respectively. Our results had a high dispersion of data points near the 1:1 line, which indicated that this model was unsuitable for slopes covered with rigid vegetation (Fig. 6a). The model did not consider the slope factor because the roughness of soil slopes increased with slope during erosion, which offset the contribution of the slope to $u$[44]. Cen et al.[17] reported a model with adj. $R^2$, NSE, and $RRMSE$ values of 0.61, 0.55, and 0.22, respectively. This model considered factors such as hydraulic radius, slope, vegetation coverage, and water depth and was more accurate than the previous model[27]. However, the equation specifically developed for modeling vegetated slope flow velocities did not assess flow velocities on bare slopes[17]. We found that the model was relatively dispersed near the 1:1 line primarily because of differences in the types of simulated vegetation (Fig. 6b). Cen et al. simulated Poaceae plants, which are softer than rigid vegetation. The influence of vegetation on the hydrodynamic properties of surface water is affected not only by the above- and under-ground parts of the vegetation[16], but also by different morphological features of the vegetation[57].

Conclusions

This study conducted indoor simulation experiments to investigate the mechanisms by which rigid vegetation coverage and growth direction affect the mean flow velocity under conditions of four slope gradients, five flow rates, four levels of vegetation coverage, and two vegetation growth directions. First, we analyzed the impact of slope and flow rate on mean flow velocity and found that both significantly affected mean flow velocity ($p < 0.05$), with mean flow velocity increasing as both slope and flow rate increase. Second, we analyzed the impact of rigid vegetation on the mean flow velocity, observing both similarities and differences with previous studies. Our results indicated that rigid vegetation coverage not only reduces the mean flow velocity but can also increases it under certain conditions, primarily owing to the compression of the water flow path by the rigid vegetation. Additionally, the mean flow velocity under the BH conditions was generally higher than that under the BS conditions, and the velocity ratio was significantly correlated with the Reynolds number ratio, resistance coefficient ratio, and flow rate ($p < 0.05$). Finally, we established a model to predict the mean flow velocity by combining vegetation equivalent roughness and the Manning formula. The results showed that this model could accurately predict the average flow velocity (adj. $R^2 = 0.87$, NSE = 0.86, $RRMSE = 0.12$).

Under natural slope conditions, the substrate conditions change with water erosion, whereas plant rhizomes and soil microorganisms alter the cohesion and structure of soil particles. These factors affect the mean slope flow velocity and, therefore, future research should try to simulate the state of slope water flow under natural conditions as closely as possible.

Declarations

Competing interests
The author declares no competing interests.

Author Contribution

Z. Cai, J. Xie, and Y. Chen contributed to the project design, performed the experiments, and wrote the manuscript. Z. Ca, J. Xie, and J. Wang contributed to data analyses, interpretation, and manuscript writing. C. Wang and Y. Yang reviewed the manuscript.

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Data Availability

Data will be made available on request. For any data inquiries, please contact the corresponding author, Professor Wang Jian, at wangjian@nwafu.edu.cn.

References


Figures
**Figure 1**

**Schematic of the experimental apparatus.** This figure depicts a schematic of the experimental apparatus used for hydrodynamic studies. Key features include: Head tank (controls the initial water inflow); Steady flow plate (ensures a consistent flow into the flume); Experiment flume (a channel where water dynamics are studied); Sandpaper (simulates rough surface conditions); Adjustable bracket (Allows slope adjustments); Outlet (Where water exits the apparatus). The setup is designed for mobility and adjustability, supporting various experimental conditions.
Figure 2

**Two different simulations of rigid vegetation. (a) Pipes were positioned perpendicular or (b) perpendicular to the horizontal plane of the slope.** This figure illustrates two setups used to simulate the impact of rigid vegetation on flow dynamics. These setups help in understanding how vegetation orientation affects water flow under different landscape conditions.

Figure 3

**Distribution of mean flow velocities under different flow rate and slope conditions.** (a) and (c) represent the distribution of mean flow velocity when perpendicular to the slope surface, with (a) showing velocities under different flow discharges and (c) under different slope angles. (b) and (d) show the distribution of mean flow velocity when perpendicular to the horizontal plane, with (b) presenting velocities at different flow discharges and (d) at different slope angles.
Figure 4

Variations in mean flow velocity across different degrees of vegetative coverage. This figure illustrates the changes in mean flow velocity (Y-axis: mean velocity in m·s⁻¹) under varying numbers of rigid vegetation (X-axis: number of rigid vegetation) and different flow rates (legend: flow rates from 5 L·min⁻¹ to 40 L·min⁻¹). Each subplot represents experimental results under different slope angles (titles: such as 5°, 10°, 15°, 20°). Different letters indicate statistically significant differences (p < 0.05) among the mean velocities at the same flow rate and slope with varying vegetation coverages. This data is useful for analyzing the impact of vegetation on fluid dynamics and the potential effects of vegetation configurations on soil erosion control.
Figure 5

**Relationships among velocity ratio and (a) Reynolds number ratio, and (b) flow rate.** This figure displays: (a) A scatter plot showing the relationship between the ratio of Reynolds numbers ($Re_{BS}/Re_{BH}$) and flow velocity ratio ($u_{BS}/u_{BH}$). Data points are categorized by the number of vegetation elements $N$ (95, 187, 286). The regression line $y = 6.66x - 5.69$ with an Adj$R^2$ of 0.70 and $p<0.01$ suggests a statistically significant linear relationship. (b) Box plots depicting flow velocity ratios across various flow discharges (5, 10, 20, 30, 40L·min$^{-1}$). The trend line $y = -0.006x - 0.753$ with an Adj$R^2$ of 0.37 and $p<0.01$ indicates a significant negative correlation between flow discharge and velocity ratio.
Figure 6

Comparison of predicted and measured values across different mean flow velocity prediction models.

(a) Based on the model from Nearing et al. [27], this panel shows the relationship between predicted and measured mean velocities under different vegetation counts (N=95, N=187, N=286). (b) Derived from the model by Cen et al. [17], this panel illustrates the comparison of predicted and measured velocities across similar vegetation densities. (c) and (d) Based on equations 18 and 29 from this study, these panels display the predicted versus measured flow velocities, also under varying numbers of vegetation. The 1:1 line in each panel represents the ideal match between predicted and measured values, where predictions perfectly align with actual measurements. The 2:1 and 1:2 lines indicate where the predicted values are double or half the actual measured values, respectively. These comparisons help to assess the accuracy and reliability of each model in practical applications.