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Impacts of grass basal diameter on runoff erosion force and energy consumption in gully bed in dry-hot valley region, Southwest China

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Abstract

Purpose Gully erosion is one of the major contributors to severe land degradation in the Yuanmou Dry-hot Valley Region, Southwest China. Grass has been proved to have great advantages in gully erosion control. This study aimed to detect the influence of grass basal diameter on change processes of runoff velocity, sediment transport rate, and runoff energy consumption.

Materials and methods A series of scouring tests were conducted based on a field experimental platform under the same flow discharge, and the impacts of different grass basal diameter (d) (0, 17, 43, 70, and 98 mm) on variations of runoff velocity (v), sediment transport capacity (S_t), and runoff energy consumption (E_c) were explored in this study.

Results and discussion The results showed that values of runoff velocity and sediment transport capacity decreased notably with the increase of grass basal diameter, and two declining power functions can be found ($v = 0.689*d$^(− 0.106), $p < 0.01$; $S_t = 0.741–2.228E\text{-}11*d$^4.701, $p < 0.01$). As for the spatiotemporal variation, the influence of grass basal diameter on runoff velocity had obvious stage features, and the influence on sediment transport capacity mainly concentrated on spatial variation in the downstream of gully bed (16^{th}–20^{th} m away from gully head). Furthermore, the increasing of grass basal diameter could effectively enhance runoff energy consumption, and a logistic growth function had been found. Finally, the grass basal diameter of 70 mm proved to be the critical grass basal diameter for effectively reducing runoff erosion force and increasing runoff energy consumption in gully beds in this study.

Conclusion These results indicate that the grass growth can effectively reduce runoff erosion force and increase runoff energy consumption, and in general, this function will be enhanced with the improvement of grass basal diameter in gully beds.

Keywords Grass basal diameter · Erosion force · Hydrodynamic properties · Energy consumption · Dry-hot valley region

1 Introduction

Gully erosion is an important soil erosion pattern, and has been recognized as one of the most important processes in sediment production and land degradation in a wide range of environment (Wijdenes et al. 2000; Poesen et al. 2003; Wu et al. 2008; Sidorchuk 2020; Agostini et al. 2022). Gully erosion encroaches upon cultivated land, damages land resources, and increases the connectivity in the landscape; furthermore, it reduces land productivity and accelerates land degradation (Poesen et al. 2003; Bennett and Wells 2019). All these variation processes caused by gully erosion can redistribute the sediment from uplands to valley bottoms and channels, which has seriously threatened the ecological and environmental security of the region (Gabris et al. 2000; Kertész and Gergely 2011). Previous studies have shown that vegetation measures can play a significant role in controlling gully erosion (Valentin et al. 2005; Malik 2008; Dong et al. 2018; Liu et al. 2019a; Gao et al. 2020). For example, Rey (2003) found that gullies were generally inactive when the cover of low vegetation was above 50% in the gully floor as a percentage of the gully floor surface; Molina et al. (2009) deemed that vegetation was the

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most important factor to accelerate sediment deposition and promote gully stability. Frankl et al. (2019) summarized that dense root systems could prevent slumping, which was an important process at gully margins, especially where soils were subjected to elevated groundwater tables. In a word, vegetation has been a widely acknowledged measure in reducing runoff and sediment yield (Fu et al. 2020).

As a kind of important vegetation measure, grass with dense amount of roots has a strong retention force on soil so that it can effectively reduce surface runoff and prevent soil erosion (Zhang and Zhou 2015; Guo et al. 2019). A series of previous studies showed that grass could exert even more advantageous effect on runoff interception and sediment reduction, particularly, in the areas with harsh natural condition and serious soil erosion (Yu et al. 2009; Wu et al. 2010; Tian 2010; Xiao et al. 2011; Dong et al. 2018). For instance, Shi et al. (2013) summarized the effects of different types of vegetation recovery on runoff and soil erosion and found that high coverage of grass prevented surface runoff and soil erosion more effectively than shrub and deciduous trees. Nevertheless, numerous literatures mainly paid predominant attention to the effect of root system (Gyssels and Poesen 2003; De Baets et al. 2006; Guo et al. 2019; Liu et al. 2019b), such that Burylo et al. (2011) and Frankl et al. (2019) deemed that plant roots could increase the resistance of soils to water erosion by improving soil properties such as organic carbon content, structure, and cohesion, and Gyssels et al. (2006) found that plant root could reduce soil detachment rates up to 50–60% compared with rootless soils. As an important part of grass, the aboveground part can also affect the interaction processes between soil and water, but there lacked a specific research about the influence of aboveground part of grass on runoff erosive dynamic process and paralleled energy consumption effects (Pan and Shangguan 2006). The few studies about aboveground portion of vegetation mainly concentrated on the effect of aboveground biomass on runoff detachment and transport capacity (Morgan 1995; Gyssels and Poesen 2003). As a vital component to convert the movement condition of overland flow, the studies about how the aboveground part of vegetation affect the runoff velocity, sediment transport capacity, and corresponding energy dissipation process need be involved. In this study, grass basal diameter was used to indicate the growth status of grass vegetation aboveground, and a series of field in-situ scouring simulation experiments were conducted to study the impacts of grass basal diameter on the spatiotemporal variation characteristics of hydrodynamic properties, and to explore the dissipating effect of grass basal diameter on runoff energy. The research results can ascertain the impact of growth status of grass aboveground on runoff hydrodynamic processes, and are of great significance to reveal the dynamic mechanism of grass growth in promoting gully stability, and furthermore can provide theoretical basis for adopting effective vegetation measures to control gully erosion in Dry-hot valley region.

2 Materials and methods

2.1 Study area

This study was implemented in Yuanmou Gully Erosion and Collapse Experimental Station (YGEES), a field station operated by the Institute of Mountain Hazards and Environment (IMHE) of the Chinese Academy of Sciences (CAS). It is located in Yuanmou Dry-hot valley region in the northern part of Yunnan Province, Southwest China, which covers an area of 2020 km^2, extending between 101°35′ E to 102°06′ E and 25°23′ N to 26°06′ N (Fig. 1). The study area is subtropical monsoon climate, and characterized with dry-hot climate, concentrated rainfall, and notable dry and wet seasons. It has an average temperature of 21.9 °C with a maximum of 42 °C. The average annual precipitation is 613.8 mm, and the potential evaporation is as high as 3640.5 mm, which is 5.9 times that of the precipitation. What's more, the rainy season lasting from June to October whose rainfall can account for 85% of the annual precipitation (Su et al. 2014), and heavy rainfall is very common in the rainy season which provides fundamental dynamic condition for the activation of gully erosion. The zonal vegetation type is tropic bushveld with scattered trees, which results in a tropical savanna-like ecosystem whose forest coverage rate is as low as 5.2% (Wang et al. 2005), and the dominate vegetation is *Heteropogon* genus. Due to the combination of rainy season's heavy rainfall and weak loose stratum in Dry-hot valley region, gully erosion is well developed, among which the average gully distribution density is 4.5 km· km^{-2} with a maximum density of 7.4 km· km^{-2}, and the soil erosion rates are estimated ranging from 8000 to 20,000 t·km^{-2}·a^{-1}(Yang et al. 2012).

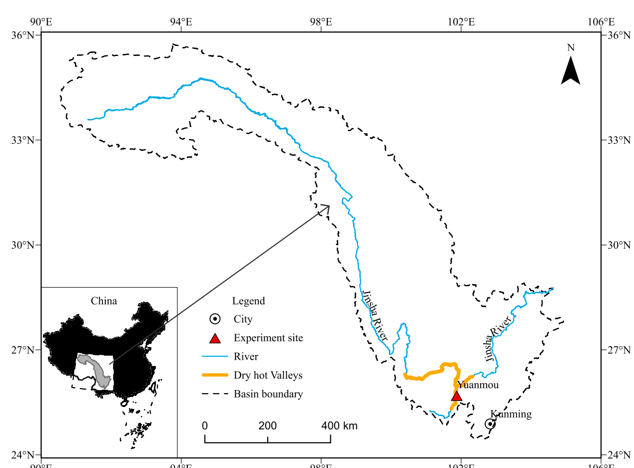


Fig. 1 The location of Jinsha Dry-hot valley in southwest China

2.2 Experiment design and data collection

To assess the impacts of the grass basal diameter on runoff erosion force (runoff velocity, sediment transport capacity) and energy consumption, a series of field in-situ scouring tests were carried out on a field experimental platform in March to April 2013 in the YGECES, CAS. The platform was constructed in a representative bank gully in Dry-hot valley region. On the basis of field investigation and in consideration of realistic feasibility, the platform's specification were determined as follows: the platform was 2-m wide with a 20-m-long downstream gully bed, a 0.5-m-high headcut and a 5-m-long upstream catchment. Mean slope gradients for gully bed and catchment were 13° and 8° with a vertical headcut, respectively (Fig. 2). The soil type of the platform was dry red soil (Ustic Ferrisols) whose bulk density was about 1.63 to 1.64 $g{\cdot}cm^{-3}$ with 79.61% sand, 12.42% silt, and 7.97% clay.

Heteropogon contortus is the dominant indigenous species in the study area and widespread in the studied Dry-hot valley region. As a dominant indigenous species, *H. contortus* has been regarded as an effective vegetation measurement to control soil erosion in Dry-hot valley region, because *H. contortus* can change the water circulation pathway of degraded soil ecosystem by strengthening rainfall infiltration, reducing runoff, cutting down soil water evaporation, and improving the water-holding capacity of litter, so as to promote and start the restoration process of corresponding ecosystem (Zhang 2005; Tang et al. 2015; Wang et al. 2016; Dagar 2018; Mata et al. 2018). In addition, *H. contortus* has been considered to have an important function in promoting active gullies tending to be stable (Zhang 2005; Hendricksen et al. 2010; Orr et al. 2010; Zhao et al. 2016). Therefore, *H. contortus* was selected for this experiment, and it was planted with an interval of 10 cm × 10 cm from the 4th meter (assuming the headcut location was the origin of the coordinate) of the downstream gully bed to the bottom of the platform. The length and width of the planted grass belt were 16 m and 2 m, respectively. Grass basal diameters of 0 (no grass), 17, 43, 70, and 98 mm were set by cutting tillers with a scissor (Fig. 3). Each of the above-mentioned grass basal diameters was identified by the integer mean value of 80 *H. contortus* through random measurement using a vernier caliper. The disposal of no grass that grass basal diameter was 0 mm indicated that the aboveground part of *H. contortus* had been fully cut off while the underground part has been kept in line with the other grass basal diameter treatments.

Each field scouring tests lasted 100 min with a flow discharge of 5.0 $m^3{\cdot}h^{-1}$, which was approximately equal to the rainfall intensity of 90 $mm{\cdot}h^{-1}$, and an equalization pond was used to keep flow discharge to be stable (Su et al. 2014; Yang et al. 2015). Surface runoff velocity (v_s, in $m{\cdot}s^{-1}$), runoff depth (h_1, in m), runoff width (w_1, in m), and runoff temperature (T_1, in °C) were measured three times directly at an interval of 10 min at every observation section. And the observation sections were set in the location of the 4th, 6th, 8th, 10th, 12th, 14th, 16th, 18th, and 20th meter of the downstream gully bed. Correspondingly, the scouring tests were performed in the same plot with a 3-day interval between every two tests, i.e., topography recovery was applied to enable the initial conditions of each test to be almost identical.

2.3 Data analysis

According to the study results of Horton (1945), mean runoff velocity (v) could be calculated by the measured surface runoff velocity (v_s) multiplying a coefficient that was determined by the value of Reynolds numbers (Re) (Eq. (1)). In this study, Re was > 2000 in each single scouring test indicating that runoff was turbulence. Therefore, the mean runoff velocity could be obtained by multiplying the measured surface runoff velocity by 0.67 (Horton 1945; Zheng and Xiao 2009).

The sediment transport capacity (S_t) of runoff is another important indicator that can reflect the runoff eroding force. Fei and Shao (2004) put forward a formula of sediment transport capacity for high concentration runoff in gullies through a series of experimental researches and comprehensive analysis. And the formula had been proven to be useful to estimate the sediment transport capacity of small

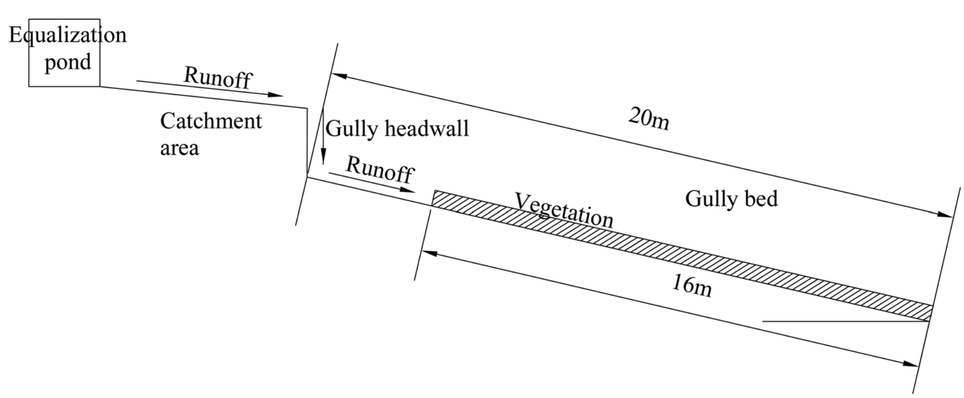
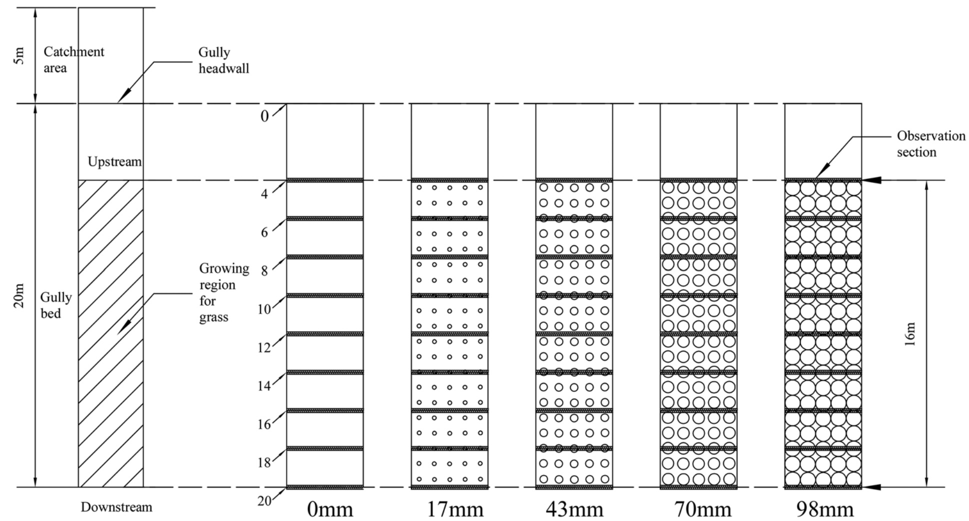


Fig. 2 Sketch map of scouring experiment plot

Fig. 3 The setting pattern of different grass basal diameter



catchments and in the planning of soil conservation measures in small watersheds (Eq. (2)).

Runoff total energy (E) contains kinetic energy and potential energy of runoff (Eq. (3)). According to the law of conservation of energy under ideal conditions, the current total energy is equal to the difference between total energy in the initial state and dissipated energy (i.e. energy consumption), in other words, the energy consumption (E_c) can be obtained by calculating the difference of total energy between every two stages. In this study, we mainly focus on the runoff energy consumption flowing through the whole grass belt, that is, the changing process of energy consumption between the first observation section (at the 4th meter of the downstream gully bed) (E_4) and the final observation section (at the bottom of the gully bed) (E_{20}) is our study object (Eq. (4)) (Foster et al. 1984; Qian and Wan 2003; Wei 2008)

$$Re = v_s r/\eta \tag{1}$$

$$S_t = 1.23(q/m)^{0.117} J^{0.333}, m = (2h + w)/h \tag{2}$$

$$E = 1/2\gamma q v^2 + \gamma q L \sin a \tag{3}$$

$$E_c = ET_4 - ET_{20} \tag{4}$$

where v_s is surface runoff velocity, in m·s^{-1}; v is mean runoff velocity, in m·s^{-1}; r is the hydraulic radius, in m; η is the water kinematic viscosity coefficient, in m^2·s^{-1}; h is the average depth, in m (Gong et al. 2010; Su et al. 2015); q is unit discharge, m^3·s^{-1}; m is sectional morphological parameter; γ is the volume weight of runoff, in kg·m^{-3}; and J is the hydraulic gradient that is equal to the sine value of the water slope; L is the length of slope, m; and α is the gradient of hillslope, rad (Foster et al. 1984; Yang 2000; Qian and Wan 2003).

Non-linear regression analysis had been used to determine relationships between the mean runoff velocity (v), sediment transport capacity (S_t) and the scouring time (t) as well as the location of observation section which was defined as the distance between observation section and gully headwall (DOH). Moreover, one-way analysis of variance was applied to test the differences among the different experiment treatments in energy consumption (E_c), and the separation of means was made according to Duncan's difference test at an alpha level of 0.05. Additionally, statistical analyses were carried out using SPSS 16.0 and Origin 8.0, and graphs were drawn with Sigma Plot software (Version 10.0).

3 Results

3.1 The change process of runoff velocity under the influence of grass basal diameter

3.1.1 Temporal variation of runoff velocity

Runoff velocity is one of the most important direct indicators to reflect the movement status of overland flow. In this study, the runoff velocity of each observation section at the same time was averaged to express the runoff movement state of the whole gully bed at that time. According to this, the temporal variation process of the average runoff velocity under the influence of different grass basal diameter was showed in Fig. 4. On the whole, as the scrouring test progressed, the runoff velocity decreased in different rates in the eartly stage and tended to be stable at the later stage under the studied five grass basal diamter.

To further analyze the change process of runoff velocity with scouring time, regression analysis was used to explore the relationship between them. The results showed that the grass basal diameter had a phased effect on the temporal variation of runoff velocity. The runoff velocity decreased as a power function with scouring time when the grass basal diameter was less than 70 mm; a cubic curve function was found between runoff velocity and scouring time when grass basal diameter increased to 70 mm; and the relationship between runoff velocity and scouring time changed to be logarithmic when grass basal diameter further increased to 98 mm (Table 1). In addition, it had a great influence on the average decrease rate of runoff velocity during the whole experiment process for grass basal diameter. The average decreasing rates for runoff velocity increased from 0.025 to 0.051 when grass basal diameter increased from 0 to 43 mm; however, the decreasing rate dropped sharply below 0.001 when grass basal diameter was greater than 70 mm. All these results demonstrated that the decreasing rate of runoff velocity could be apparently accelerated with grass basal diameter increasing from 0 to 43 mm, but the decrease rate cannot be further increased significantly when grass basal diameter was equal to or greater than 70 mm. The main reason was that the runoff velocity and its variation amplitude were overall very small when grass basal diameter was equal to or greater than 70 mm in this study.

Table 1 The relationship between runoff velocity (v, in $m \cdot s^{-1}$) and scouring time (t, in min) under different grass basal diameters (d, in mm)

Grass basal diameter (mm)	Equation	*Adj. R*^{2}	*P*	*N*
0	$v = 0.559 * t$^(−0.044)	0.342	< 0.01	10
17	$v = 0.587 * t$^(−0.038)	0.297	< 0.01	10
43	$v = 0.610 * t$^(−0.084)	0.732	< 0.01	10
70	$v = 5.409$*E-7*t^3–8.702*E-5*t^2 + 0.004*t + 0.431	0.158	< 0.01	10
98	$v = 1.297$–0.158*ln(t + 227.141)	0.223	< 0.01	10

The range and variable coefficient were two important indicators reflecting time stability of runoff velocity. In detail, the range of runoff velocity was respctively, 0.104, 0.009, 0.135, 0.058, and 0.080, and the variable coefficient was respctively, 0.063, 0.058, 0.091, 0.039, and 0.067, under grass basal diameter of 0, 17, 43, 70, and 98 mm. As described, both range and variable coefficient of runoff velocity were the least under grass basal diameter of 70 mm while turned to be the largest under that of 43 mm. However, it is worth mentioning that there had no regular influence of grass basal diameter on the time stability of runoff velocity. Despite these, it also can be concluded that the time stability

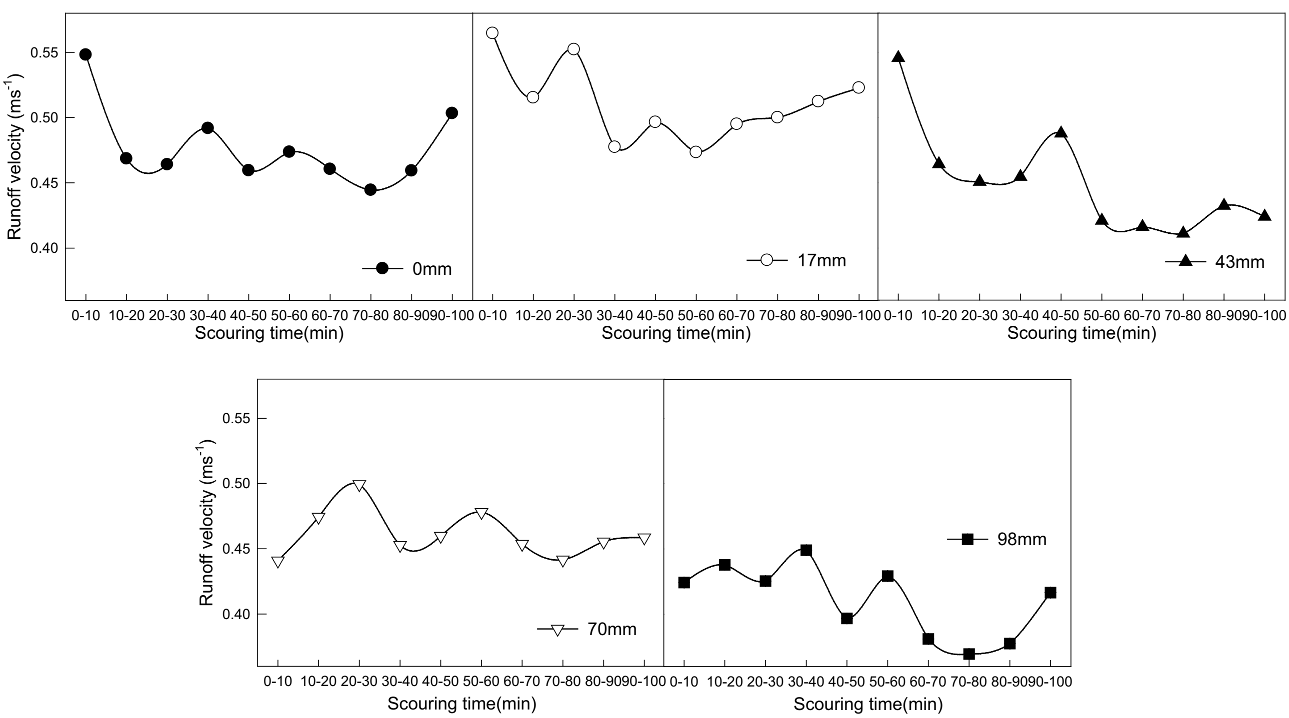


Fig. 4 The variation of runoff velocity (v, in $m \cdot s^{-1}$) with scouring time (t, in min) under different grass basal diameters (d, in mm)

of runoff velocity was the strongest under grass basal diameter of 70 mm while that was the weakest under 43 mm.

3.1.2 Spatial variation of runoff velocity

The spatial variation processes of runoff velocity under the five treatments of grass basal diameter were quite different (Fig. 5). As a whole, runoff velocity experienced a first fluctuation decreasing followed by a rapid increase, and then converted to decrease again along with the extending direction of gully beds under grass basal diameter of 0 mm, 17 mm, and 43 mm. However, there were still some differences in the detailed variation processes among the above-mentioned three grass basal diameter treatments. When grass basal diameter was 0 mm, runoff velocity had slight variation within the 4^{th} –10^{th} meter of gully bed, fluctuated likely periodically within the 10^{th}–16^{th} meter, and then increased sharply to the peak of 0.603 $m \cdot s^{-1}$ at the observation section of the 18^{th} meter. As for grass basal diameter of 17 mm, runoff velocity decreased with a power function within the 4^{th}–16^{th} meter in the gully bed ($v = 0.736*DOH$^(-0.186), $p < 0.01$), whereas runoff velocity showed an obvious trend of first increasing and then decreasing within the 16^{th}–20^{th} meter among which runoff velocity reached the maximum value of 0.644 $m \cdot s^{-1}$ at the 18^{th} meter of the gully bed. With regard to grass basal diameter of 43 mm, runoff velocity was approximately stable within the 4^{th}–8^{th} meter, decreased within the 8^{th}–10^{th} meter, and then had an obvious trend of first increase and then decrease within the 10^{th}–20^{th} meter in which the peak value of runoff velocity was 0.529 $m \cdot s^{-1}$ at the observation section of the 16^{th} meter in gully bed. All the above-mentioned observations demonstrated that there were similarities in general variation rules, but differences in local details for the spatial variation processes of runoff velocity under grass basal diameter of 0 mm, 17 mm, and 43 mm, that is, runoff velocity showed different downtrends in the upstream of gully beds (4^{th}–16^{th} meter for grass basal diameter of 0 mm and 17 mm, 4^{th}–10^{th} meter for grass basal diameter of 43 mm), meanwhile tended to firstly increase and then decrease in the downstream of gully beds (16^{th}–20^{th} meter for grass basal diameter of 0 mm and 17 mm, 10^{th}–20^{th} meter for grass basal diameter of 43 mm). In particular, the maximum values of runoff velocity under the treatments of 0 mm (0.603 $m \cdot s^{-1}$) and 17 mm (0.644 $m \cdot s^{-1}$) were very close and both appeared at the 18^{th} meter of gully bed, correspondingly, the maximum value under treatment of 43 mm was 0.529 $m \cdot s^{-1}$ which appeared at the 16^{th} meter. These results suggested that the increasing of grass basal diameter can reduce the peak value of runoff velocity and promote the peak location move upstream in gully beds.

As a contrast, great difference in spatial change processes of runoff velocity under grass basal diameter disposals of 70 mm and 98 mm had also been found in Fig. 5. As for grass basal diameter of 70 mm, runoff velocity almost fluctuated

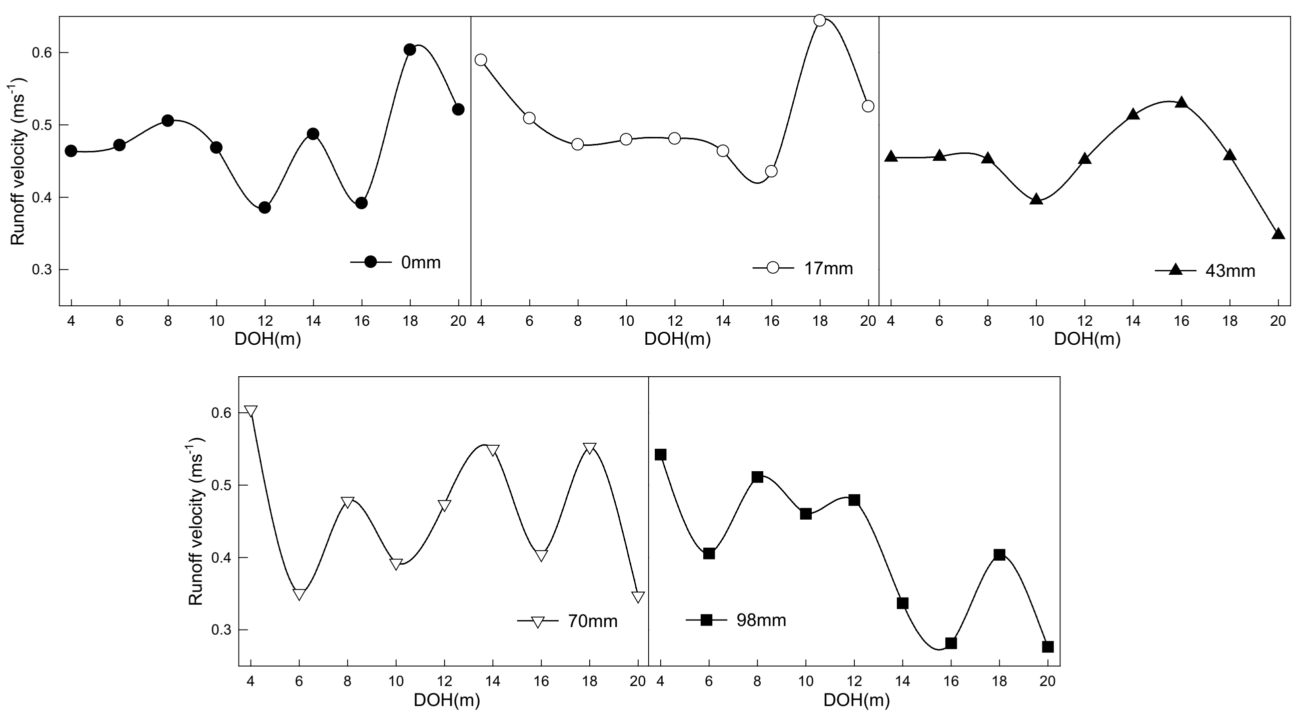


Fig. 5 The variation of runoff velocity (v, in $m \cdot s^{-1}$) with the distance between observation section location and gully headwall (DOH, in m) in the gully bed under different grass basal diameters (d, in mm)

around the 0.461 $m \cdot s^{-1}$ along the gully bed, and presented a trend of increase–decrease-increase–decrease periodically. However, under the treatment of 98 mm, the runoff velocity showed an exponential decrease process along with the gully bed ($v = 0.601*0.968$^DOH, $p < 0.01$). According to the above analysis, it can be seen that the spatial change process of runoff velocity was affected greatly by grass basal diameter.

The average value of runoff velocity in the whole gully bed and experiment process can comprehensively reflect the moving state of runoff in gully bed. On the basis of this, regression analysis was used to detect the relationship between runoff average velocity and grass basal diameter, and the result indicated that average runoff velocity showed a power decline trend with grass basal diameter: $v = 0.689*d$^(-0.106), $p < 0.01$ (Fig. 6). Furthermore, the mean reduction rate of runoff velocity was about 0.0005 when grass basal diameter was less than 70 mm, and it increased to 0.0018 which was about 3.6 times higher than the former when grass basal diameter was greater than 70 mm. Therefore, it could be found that the mean rate of runoff velocity reduction was really different when grass basal diameter was less and greater than 70 mm. All these results suggested that the increase of grass basal diameter can notably cut down the average runoff velocity in the whole gully bed which can, to some extent, protect gully bed from intensive erosion.

3.2 The change process of runoff sediment transport capacity under the influence of grass basal diameter

3.2.1 Temporal variation of sediment transport capacity

As an important indicator that can evaluate runoff carrying capacity, runoff sediment transport capacity reflects the ceiling of runoff in carrying sediment under a certain flow state. Figure 7 showed the temporal change processes of sediment transport capacity under five treatments of grass basal diameter. On the whole, sediment transport capacity tended to firstly increase and then become basically stable over the later experiment time, and the pattern of temporal change process of sediment transport capacity could be fitted by the power function satisfactorily (Table 2).

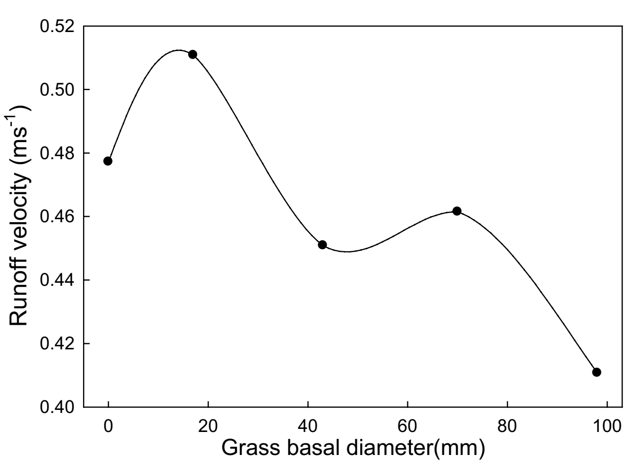


Fig. 6 The variation of average runoff velocity (v, in $m \cdot s^{-1}$) with grass basal diameters (d, in mm)

Despite the above-described observations, it was worth mentioning that the detailed temporal change process for sediment transport capacity had some differences under the grass basal diameter of 0 mm, 17 mm, 43 mm, 70 mm, and 98 mm. With regard to grass basal diameter of 0 mm, the sediment transport capacity increased linearly at a rate of about 0.004 within 0–40 min, and then stopped increasing and stabilized around 0.766 within 40–100 min. When grass basal meter was 43 mm, the sediment transport capacity showed a continuous increase in 0–50 min with an average increase rate of 0.002, and was stable around 0.755 in the following 50–100 min. When grass basal meter was 70 mm, the sediment transport capacity increased at an average rate of 0.001 within 0–60 min, then decreased to some extent and stabilized around 0.743 within 70–100 min. As for grass basal diameter of 98 mm, the sediment transport capacity just had a short increase within 0–20 min, and then was basically stable around 0.689 in the subsequent 20–100 min. Separately, the sediment transport capacity under grass basal diameter of 17 mm mainly showed a periodical fluctuation trend, and the fluctuation amplitude had a decrease in processes, among of which, the fluctuation range of sediment transport capacity decreased from 0.055 in 0–50 min to 0.030 in 50–100 min, specifically the sediment transport capacity basically stabilized around 0.755 in 50–100 min.

Further analysis found that sediment transport capacity in the relative stabilize stage declined from 0.766, 0.755, and 0.755 to 0.743 and 0.689 when grass basal diameter increased from 0 mm, 17 mm, and 43 mm to 70 mm and 98 mm, which was probably because grass belt can change runoff movement pathway and disperse runoff, thereby reducing flow depth and reshaping flow pathway. In addition, the duration of sediment transport capacity's continuous increase were respectively 40 min, 50 min, and 60 min for grass basal diameter of 0 mm, 43 mm, and 70 mm, namely there was a positive correlation between the duration of the increase processes of sediment transport capacity and grass basal diameter. However, the duration just lasted 20 min for grass basal diameter of 98 mm which might result from sediment transport capacity that was overall at a low level under this treatment.

In conclusion, there were some differences in the temporal change process of sediment transport capacity under different grass basal diameter treatments, but the overall change rule was basically similar that they all showed the trend of increase first and then stabilizing. This was mainly because sheet flow with small depth was the major component of

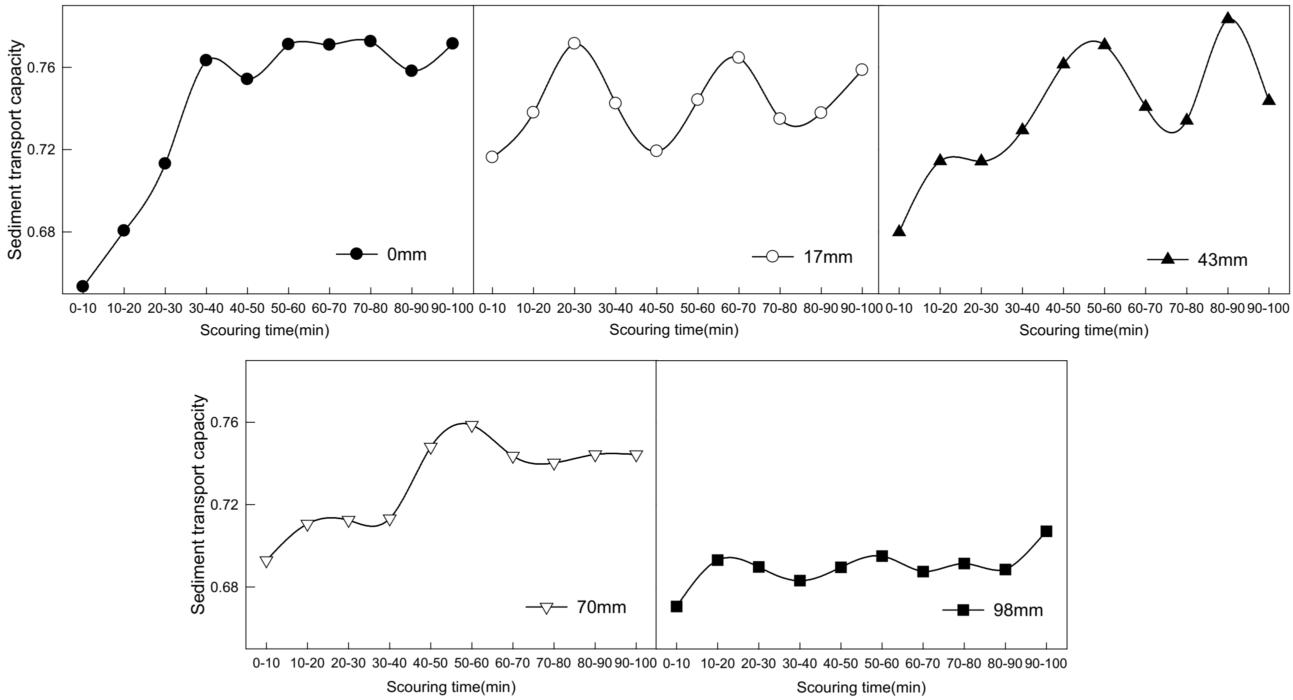


Fig. 7 The variation of sediment transport capacity (S_t) with scoring time (t, in min) under different grass basal diameters (d, in mm)

overland flow in the early stage of our experiments. As the experiment progressed, concentrated flow gradually replaced sheet flow as the main part of overland flow, and the runoff depth corresponding had an increasing process. Hence, sediment transport capacity had an increasing trend in the early phase of the experiment. However, as the main runoff pathway and concentrated flow tended to be stable, the average runoff depth no longer increased, and the major role of overland flow was to shape the morphology of cross section in the later stage of the experiments. As a consequence, cross section morphology, runoff depth and hydraulic gradient gradually achieved a dynamic equilibrium state which promoted sediment transport capacity tending to be stable.

Table 2 The relationship between sediment transport capacity (S_t) and scouring time (t, in min) under different grass basal diameters (d, in mm)

Grass basal diameter (mm)	Equation	*Adj. R*^{2}	*P*	*N*
0	$S_t = 0.592*t$^0.061	0.871	< 0.01	10
17	$S_t = 0.715*t$^0.011	0.055	< 0.01	10
43	$S_t = 0.642*t$^0.038	0.641	< 0.01	10
70	$S_t = 0.659*t$^0.029	0.727	< 0.01	10
98	$S_t = 0.664*t$^0.019	0.426	< 0.01	9

3.2.2 Spatial variation of sediment transport capacity

Obvious difference can be found for the change processes of sediment transport capacity along with the gully beds under different grass basal diameter (Fig. 8). For grass basal diameter of 0 mm, sediment transport capacity tended to increase firstly and then to be stable along with the gully bed, and a power function can be found between the two ones ($S_t = 0.594*DOH$^0.093, $p < 0.01$), and sediment transport capacity was basically stable in the vicinity of 0.784 within the 16th–20th meter of the gully bed. As for grass basal diameter of 17 mm, sediment transport capacity fluctuated around 0.753 with an amplitude of 0.063 within the 4th–16th meter in the gully bed ($S_t = 0.721 + 0.063*\sin((DOH + 2.910)\pi/3.211)$, $p < 0.01$); in addition, sediment transport capacity increased to some extent and stabilized around 0.778 within the 16th–20th meter of gully bed. When grass basal diameter was 43 mm and 70 mm, similar change processes can be found, i.e., sediment transport capacity fluctuating increased firstly and then tended to decrease along with the gully bed. Even so, there was notable difference for the maximum values of sediment transport capacity and its position in the gully bed between the two grass basal diameter treatments. Specifically, the maximum values of sediment transport capacity were respectively, 0.838 and 0.809, at the 16th meter and 18th meter of gully bed under the grass basal diameter of 43 mm and 70 mm. As for grass basal diameter of 98 mm, the sediment transport capacity increased

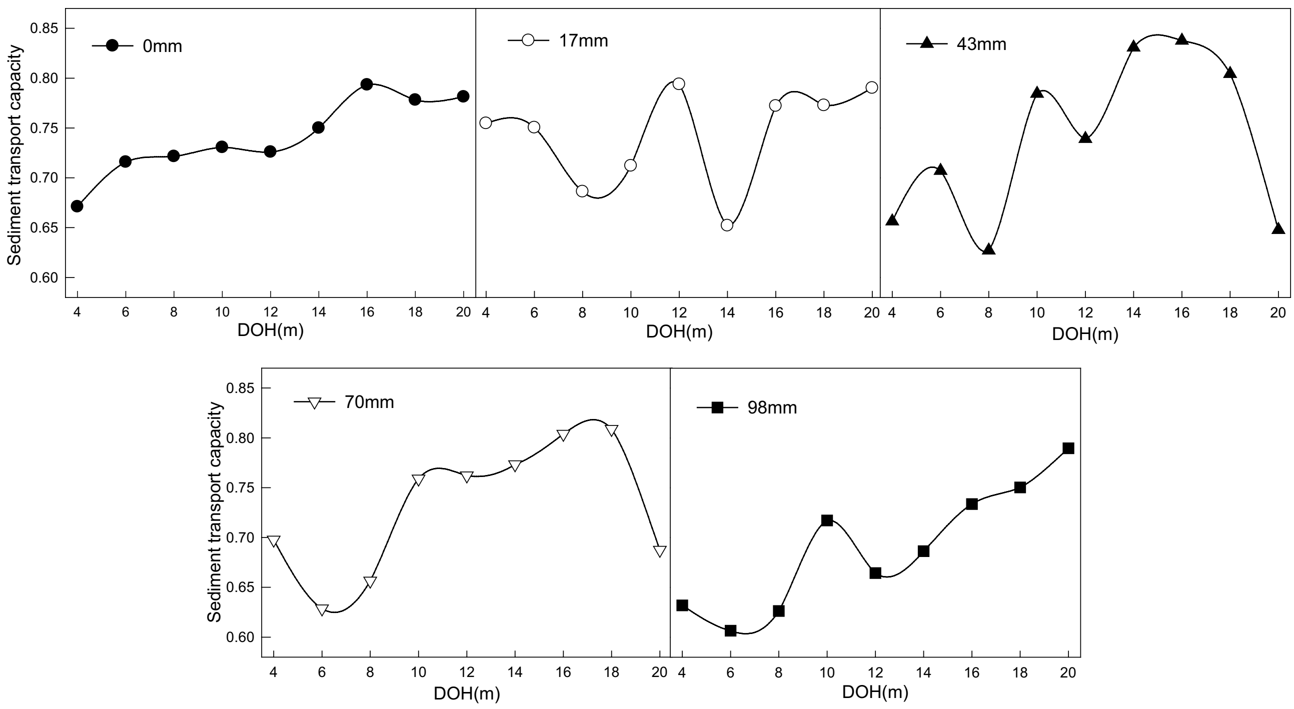


Fig. 8 The variation of sediment transport capacity (S_t) with the distance between observation section location and gully headwall (*DOH*, in m) in the gully bed under different grass basal diameters (*d*, in mm)

continuously along with the extending direction of gully bed, and an extremely significant linear relationship can be detected between them ($S_t = 0.553 + 0.011*DOH$, $p < 0.01$). It can be seen from the above analysis that sediment transport capacity all showed an increasing trend despite that the increasing patterns had a little difference in the upstream of the gully bed (4th–16th meter), in contrast, the variation processes of sediment transport capacity were quite different in the downstream of the gully bed (16th–20th meter) under the five grass basal diameter treatments ($d \leq 17$ mm, S_t was basically stable; 43 mm $\leq d \leq 70$ mm, S_t had an obvious decrease trend; $d = 98$ mm, S_t had an increase trend). All the above-mentioned observations demonstrated that the impact of grass basal diameter on the spatial change processes of sediment transport capacity was mainly concentrated in the downstream of gully bed.

In order to further explore the influence of grass basal diameter on sediment transport capacity, regression analysis was used to detect the relationship between the two ones, and the result showed that the average sediment transport capacity decreased with the increase of grass basal diameter as a power function ($S_t = 0.741–2.228E\text{-}11*d$^4.701, $p < 0.01$) (Fig. 9). It can also be found that there was just a little decrease trend for sediment transport capacity when grass basal diameter increased from 0 to 70 mm, and the average decrease rate of sediment transport capacity was about 0.0002, in contrast, the average decrease rate rose to 0.0015 when grass basal diameter increased from 70 to 98 mm, and the latter was 7.5 times higher than the former. All these results indicated that increasing the grass basal diameter can effectively reduce the average sediment transport capacity of runoff in gully bed, however, only when the grass basal diameter increased to a certain extent (> 70 mm in this study) could the runoff sediment transport capacity be significantly reduced.

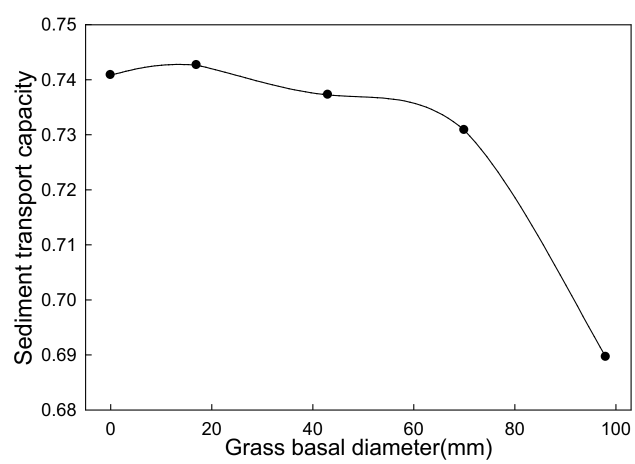


Fig. 9 The variation of average sediment transport capacity (S_t) with grass basal diameters (*d*, in mm)

In conclusion, grass basal diameter had a significant influence on the spatial and temporal variation, and the grass basal diameter had a phased function to reduce average sediment transport capacity, i.e. sediment transport capacity decreased very slowly when grass basal diameter was equal to or less than 70 mm, but the decrease rate of sediment transport capacity had a quite increase when grass basal diameter was greater than 70 mm, that is to say, grass basal diameter of 70 mm may be the critical value that can significantly accelerate sediment transport capacity reducing.

3.3 The change processes of runoff energy consumption under the influence of grass basal diameter

Runoff energy consumption reflects the energy consumed by the interaction between runoff and earth surface during the movement of runoff. The higher the energy consumption, the better the energy dissipation effect of grass basal diameter is. It can be seen from Fig. 10 that runoff energy consumption increased slowly firstly, then experienced a rapidly rising process, and then tended to be basically stable with the increase of grass basal diameter. Furthermore, a logistic curve can be used to describe the relationship between energy consumption and grass basal diameter (E_c = 3.049–0.997/(1 + (*d*/48.630)^7.931), $p < 0.01$). According to the above analysis, it can be seen that runoff energy consumption increased very slowly and almost remained at a low level when grass basal diameter was ≤ 17 mm; meanwhile, the energy consumption increased rapidly at an increase rate of 0.018 while grass basal increased from 17 to 70 mm; furthermore, runoff energy consumption almost stabilized around 3 $J \cdot s^{-1}$ rather than having continuing increase when the grass basal diameter furtherly increased from 70 to 98 mm. In order to determine what grass basal diameter can exert the most effective function in dissipating runoff energy, one-way ANOVA was conducted among the five disposals. The results showed that runoff energy consumption in grass basal diameter of 70 mm and 98 mm was significantly greater than those of 0 mm, 17 m, and 43 mm (Table 3), which indicated that only when grass basal diameter increased to a certain degree (≥ 70 mm in this study) can the runoff energy consumption be effectively increased.

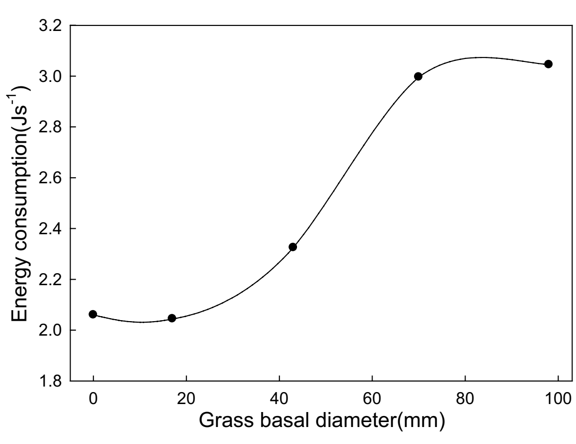


Fig. 10 The variation of runoff energy consumption (E_c) with grass basal diameters (*d*, in mm)

4 Discussion

Gully erosion is an intensive erosion phenomenon caused by serious imbalance of water and soil elements. The growth of *H. contortus* not only has a positive and long-term effect on the change and restoration of degraded soil system (Zhu 2005; Duan et al. 2017), but also has an important influence on the change of the movement condition and hydrodynamic processes of surface runoff (Wu et al. 2018). Therefore, on the basis of previous research experience and field practice, this study preliminarily discussed the influence of the basal diameter of *H. contortus* on the runoff hydrodynamic properties and paralleled dissipating effect on runoff energy in gully bed. The results showed that the basal diameter of *H. contortus* could not only change runoff erosion force (runoff velocity and sediment transport capacity) and energy consumption, but also significantly affect the spatiotemporal variation processes of erosion force. Specifically, significant declining functions were found for runoff velocity and sediment transport capacity with the increasing of grass basal diameter (v = 0.689**d*^(-0.106), $p < 0.01$; S_t = 0.741–2.228E-11**d*^4.701, $p < 0.01$), meanwhile, it had been found that runoff energy consumption would increase as a logistic growth function with grass basal diameter increasing. In addition, there was periodical or partial influence of grass basal diameter on the spatiotemporal variation processes of erosion force. Furthermore, in view of the comprehensive influence of grass basal diameter on runoff erosion force and energy consumption, the grass basal diameter of 70 mm was found to be the critical value for effectively reducing sediment transport capacity and enhancing energy consumption in this study.

Table 3 Results of one-way ANOVA for runoff energy consumption (E_c) under different grass basal diameters (*d*, in mm). Duncan's multiple range test was adopted for one-way ANOVA; Different small letters denote significant difference at 0.05 level

Grass basal diameter (mm)	Energy consumption
17	2.044a
0	2.060a
43	2.325a
70	2.996b
98	3.045b

In this study, the erosion force (runoff velocity and sediment transport capacity) can all be reduced by the increase of grass basal diameter, which was mainly because grass stems had changed the gathering processes of runoff and a series of hindering effect on runoff was formed around each grass stems. The comprehensive interaction of these hindering effects can be enhanced by the increase of grass basal diameter so as to cut down the runoff velocity and depth. Moreover, the micro-topography of runoff flowing pathway can be reshaped to some degree because the interference role of grass stems, thus sediment transport capacity had a declining trend with the increase of grass basal diameter. In addition, the possible reason, for energy consumption improved by the increasing of grass basal diameter, is the existence of grass that can effectively increase surface resistance through itself and related reshaping effect on pathway so that the greater the grass basal diameter, the larger the increase role of surface resistance. With regard to the periodical influence of grass basal diameter on the spatiotemporal variation processes of erosion force, there may be two main reasons. Firstly, the process of soil–water interaction is complicated, and the interaction between soil and water would become more and more complicated due to the change of runoff movement state and micro-topography caused by vegetation growth. Secondly, under a certain initial condition of soil and water flow, the degree to which vegetation changes the soil–water interaction process is related to the growth status of vegetation, that is, the variation processes of runoff erosion force parameters will change along with the difference of grass basal diameter. Additionally, the grass basal diameter of 70 mm was perceived as a critical value in cutting down erosion force and increasing energy consumption. On the one hand, the underlying reason was that the decrease rates of erosion force had an inflection point when grass basal diameter was 70 mm. To be specific, the decrease rates of runoff velocity and sediment transport capacity were respectively − 0.0005 and − 0.0002 when grass basal diameter was less than 70 mm; in contrast, the declining rates increased to be respectively − 0.0018 and − 0.0015 when grass basal diameter was larger than 70 mm, and the latter were about 3.6 and 7.5 times higher than the former. On the other hand, the increasing rate (about 0.0136) of energy consumption was very high when grass basal diameter was less than 70 mm; meanwhile, the energy consumption cannot be enhanced anymore and basically stabilize around 3 $J\cdot s^{-1}$ when it was greater than 70 mm. Therefore, the grass basal diameter of 70 mm was considered as the critical value, which was in line with the principle that everything may have its own limits in the objective world.

From wide view of literatures, most studies focused on the effects of vegetation coverage (Zhou et al. 2006; Wen et al. 2010; Chen et al. 2019), vegetation types (Huang et al. 2012; Shi et al. 2013; Jia et al. 2019), and planting patterns or distributions (Rey 2003; Spaan et al. 2005; Wang et al. 2014; Zhang et al. 2018b) on surface runoff and erosion processes, but almost few studies played specific attention on the dynamic processes of runoff erosion caused by the growth status of aboveground part of grass cover (Yang et al. 2017). The results of previous researches on aboveground vegetation stem mainly involved in open channel under the laboratory condition (Zhang et al. 2018a). For example, Kothyari et al. (2009) conducted an experimental study on sediment transport by channel flows with tall rigid stems whose surface was smooth, and discussed the influence of stem areal densities based on a series of flume experiments at a laboratory; Zhang et al. (2018a) emphatically explored the influence of vegetation stem diameter on flow resistance in a rectangular water channel, in which the studied vegetation consisted of polymethyl methacrylate; Zhao et al. (2016) also conducted a laboratory flume experiment to quantify the effects of vegetation stems on Reynolds number, Froude number, flow velocity and hydraulic resistance of silt-laden overland flow, and the vegetation stems were simulated by cylinders that were glued onto the flume bed. In summary, the studies on aboveground part of vegetation were all conducted by laboratory flumes with unreal vegetation stems made of composite materials, which was quite different from the reality. Therefore, this study had been innovative in exploring the influence of real grass basal diameter on runoff hydrodynamic properties under the field condition.

However, it is worth mentioning that this study mainly focused on the influence of the growth of *H. contortus* on the hydrodynamic processes of runoff, and did not study the change processes of the soil environment and the corresponding ecosystem in the gully bed during the growth of *H. contortus*, which made the changing processes of "water-soil" dual factors become one of the key directions of our future study. In addition, in view of this study is an exploratory experimental research which was conducted as soon as the growth status has been satisfying the basic requirements of experiments, hence this study had not taken into consideration the influence of different planting years of *H. contortus* on runoff hydrodynamic processes. Meanwhile, because the *H. contortus* was planted with uniform width and length in gully bed, the spatial distribution features of *Heteropogon contortus* was different from that in natural field condition, which may lead to a certain scale effect on the experimental results, and the corresponding scale effects would be taken into account in the subsequent studies. Furthermore, this study innovatively focused on the influence of grass basal diameter on hydrodynamic properties of runoff in gully bed, but due to the limitation of our experimental conditions, this study could only have conducted multiple tests based on the same experimental plot. In order to ensure the initial topography of each single test as consistent as possible, a series of useful measures such as "filling-tamping-filling-wetting-retamping-natural drying" were adopted, although the duration of sedimentation and insolation was still insufficient which would influence the experiment results.

5 Conclusions

This study explored the influence of grass basal diameter on runoff velocity, sediment transport capacity, and energy consumption as well as their spatiotemporal dynamic processes. The results showed that runoff velocity and sediment transport capacity decreased significantly with grass basal diameter as power functions ($v = 0.689*d$^($-$0.106), $p < 0.01$; $S_t = 0.741–2.228\text{E-}11*d$^4.701, $p < 0.01$), and runoff energy consumption can be enhanced by increasing grass basal diameter. The relationship between runoff energy consumption and grass basal diameter satisfied the logistic growth function ($E_c = 3.049–0.997/(1 + (d/48.630)$^7.931), $p < 0.01$). The decrease rates of runoff velocity and sediment transport capacity as well as the increase rate of runoff energy consumption were respectively, 0.0005, 0.0002, and 0.018, when grass basal diameter was less than or equal to 70 mm. The decrease rates of runoff velocity and sediment transport capacity increase to be 0.0018 and 0.0015, and the runoff energy consumption almost stabilized around 3 $\text{J}\cdot\text{s}^{-1}$ when grass basal diameter was larger than 70 mm. Furthermore, the influence of grass basal diameter on runoff velocity and sediment transport capacity was very different, and the spatial dynamic processes were affected more than the temporal variation processes of runoff velocity and sediment transport capacity by grass basal diameter. On the whole, grass basal diameter did not change the general rules of temporal dynamic processes of runoff velocity and sediment transport capacity. In contrast, the specific change processes of runoff velocity and sediment transport capacity differed from one grass basal diameter to another. In detail, the impact of grass basal diameter on the spatial change process of sediment transport capacity was mainly concentrated in the downstream of gully bed (16^{th}–20^{th} meter away from gully head). Finally, the grass basal diameter of 70 mm had been regarded as the critical condition for effectively reducing runoff erosion force and increasing runoff energy consumption as well as changing their spatiotemporal change processes.

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Declarations

Conflict of interest The authors declare no competing interests.

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