Slope- watershed coupling simulation under different vegetation coverage based on GAST model

Yongde Kang[a], Jingming Hou[a*], Yu Tong[a], Baoshan Shi[a], Zhanpeng Pan[a]

a. State Key Laboratory of Eco-hydraulics in Northwest Arid Region of China; School of Water Resources and Hydroelectric Engineering, Xi’an University of Technology, Xi'an 710048, China;

Corresponding Author: jingming.hou@xat.edu.cn

Abstract

A non-equilibrium sediment transport soil erosion model based on finite volume method (FVM) coupled with two-dimensional hydrodynamic process is proposed, application of the GPU techniques in the numerical model, making it possible to simulate the sediment transport and bed evolution in a high resolution but efficient way. The first-order Gudonov format FVM is used to discreting the control equation. The variables on both sides of the unit interface are obtained by limiting slope interpolation. An efficient and robust non-negative depth reconstruction algorithm is used to solve the dry-wet boundary problem. This algorithm makes the model have second-order accuracy in space, and also effectively suppresses the numerical oscillation. Harten, Lax van Leer Contact (HLLC) approximate Riemann solver is used to calculate mass and momentum flux, and the friction source term is calculated by the proposed split point implicit method. These values are evaluated by a novel 2D edge-based MUSCL scheme. The code is programmed using C++ and CUDA, which can be run on GPU to greatly accelerate the calculation speed. In this paper, two numerical experiments show that the model performs well in accuracy and robustness of the algorithm in the process of slope erosion and watershed erosion. The constructed model can simulate the soil erosion of slope and watershed gully under different vegetation coverage, and characterize the erosion process of interaction between slope and gully.

Keywords: Vegetation coverage; Soil erosion; FVM; Watershed erosion assessment;

1. INTRODUCTION

Soil erosion is a complex topographic process, which is caused by many factors, including rainfall intensity, duration, soil moisture,and so on (Luetzenburg et al., 2020; Li et al., 2020; Khaleghi and Varvani, 2018). Reasonable vegetation structure can effectively reduce, prevent soil erosion and improve soil properties (Pan et al., 2007;Garcia-Ruiz, 2010; Nadal-Romero E et al., 2011).Increasing vegetation coverage by vegetation restoration is one of the important measures to reduce soil erosion in high erosion risk areas(Wang et al., 2012;Duan et al., 2016), soil erosion is affected by vegetation cover types, spatial distribution and aboveground and underground roots(Shi et al., 2013; Wei et al., 2014;Duan et al., 2016; Gyssels et al., 2005; Vannoppen et al., 2015). Vegetation coverage mainly affects soil infiltration and runoff velocity(Dunkerley, 2000). The aboveground growth part of vegetation can intercept rainfall and reduce the splash erosion energy of raindrops to achieve the purpose of controlling erosion. The underground growth roots increase soil organic matter and porosity, and enhance soil erosion resistance(Wainwright et al., 2000; Zhao et al., 2015).

Over the past decade, a large number of studies have explored the impact of spatial distribution of vegetation cover on soil erosion at the experimental scale (Rey, 2003; Ruiz-Sinoga et al., 2010; Wei et al., 2014). Studies have found that the effects of different vegetation cover and vegetation distribution positions on soil erosion are also significantly different (Boer and Puigdefa´bregas.2005; Gyssels et al., 2002; Zhou and Shangguan.2007). For example, if the vegetation is located in the upper and middle parts of the slope, the erosion degree of the lower part of the slope is stronger than that of the middle part of the slope(Wei et al., 2014; Ding and Li, 2016).

Many studies have been carried out on the relationship between vegetation coverage and soil erosion (Dunne et al. 1978; Snelder and Bryan 1995), the influence of vegetation on hydraulic parameters and soil properties, and the effect of vegetation on water and sediment reduction (Zhang et al., 2017).In the study of hydrodynamic parameters and soil erosion, hydraulic parameters such as slope flow velocity, slope depth, Reynolds number, Freud number and resistance coefficient are mainly used to characterize the hydraulic characteristics of slope (Huang J et al., 1996; Hessel R et al., 2007; Ali M et al.,2013; Zi T et al., 2016). At present, the research on hydraulic characteristics of slope mainly focuses on rainfall intensity, velocity, underlying surface conditions and slope surface by means of artificial rainfall simulation

(Engman E T et al., 1986; Mohamoud Y M et al., 1992), hydraulic erosion, hydrological model and numerical simulation (Zhang et al., 2012). Under the conditions of slope and slope change, the characteristics of hydraulic characteristic parameters of slope surface and the relationship between hydraulic characteristic parameters are studied(Cerda. 1998; Zhang et al., 2012). The change of underlying surface conditions will significantly affect the hydraulic characteristics of slope flow. Affected by soil texture, gravel distribution, vegetation type, vegetation coverage and spatial pattern, the potential surface conditions and slope gradient of the slope will change, thus affecting the hydraulic characteristics of the slope. Larger slope roughness element will increase the resistance of slope flow, delay the speed of slope flow, increase the depth of slope flow, and make the flow pattern change from rapid flow to slow flow (Liu et al.,2010; Wu et al., 2011).

As an effective tool for predicting soil erosion and guiding the allocation of soil and water conservation measures, soil erosion model is an advanced field of soil erosion discipline and an effective means for quantitative research on soil erosion process. Many soil erosion models have been applied to study the process of soil erosion (Heng B C et al., 2009; Dun S et al., 2010; Renard K G et al., 1997; De Roo A et al., 1996; Morgan R P C et al., 1998). On the basis of summarizing the research results of foreign soil erosion models, domestic scholars have developed a targeted soil erosion model. Yang et al (2012) and Rompaey et al (2001) although considered channel erosion, but there were problems such as ignoring channel deposition, low prediction accuracy and unstable simulation results.

In-depth study on the process and dynamic mechanism of soil erosion under different vegetation cover is the basis for understanding the dynamic mechanism of vegetation affecting soil erosion and the relationship between water and sediment and its temporal and spatial changes. Although Tayfur (2007) and An and Liu (2009) proposed a one-dimensional and two-dimensional coupling model to simulate rainfall runoff and slope erosion, the model regards the slope as a series of two-dimensional parallel grids to the slope and decomposes it into a combination of one-dimensional cases. However, these two models are only applicable to simple slope erosion. Nord and Esteves (2005) also proposed a two-dimensional slope model coupled with rainfall-runoff-soil erosion. However, these models did not clearly distinguish between rill erosion and inter-rill area, and the solution of this model was time-consuming and could not be universally applicable. Therefore, the purpose of this study is to develop a simple and effective rainfall runoff-slope erosion model coupled with two-dimensional hydrodynamic processes to simulate the spatial distribution of slope erosion under different vegetation cover, that is the GPU Accelerated Surface Water Flow and Transport (GAST) model, and then expand it to different scales of watersheds to evaluate slope channel erosion under different vegetation cover. It is hoped that the model proposed in this study can provide a more realistic and accurate qualitative method for soil erosion prediction under different vegetation coverage at slope-basin scale.

2. MATERIALS AND METHODS

2.1 Governing equation

The finite volume method is used to establish a two-dimensional water-sediment coupling model on the slope under moving bed conditions, which is used to simulate the unsteady flow of water and the transport of viscous sand in the process of slope erosion. The model is a fully coupled model of water and sediment, considering the influence of sediment density and topography on flow movement. The central upwind scheme is used to solve the interface flux, and the linear reconstruction of the interface variable is combined to make it have second-order accuracy in space. The model uses the unbalanced (unsaturated) sediment transport formula to calculate the sediment transport process. In the whole calculation process, the model can ensure that the calculated water depth is non-negative, and has strong stability and robustness. At the same time, combined with the physical model test of indoor slope rainfall erosion, the constructed water and sediment numerical model is further verified, which confirms and deepens the mechanism of slope soil erosion process, and provides an effective tool for the development of slope erosion model and further regulation and mitigation of soil erosion. Nonlinear hyperbolic, the control equation can be written in the following vector form:

$$\frac{\partial \boldsymbol{q}}{\partial t}+\frac{\partial \boldsymbol{F}}{\partial x}+\frac{\partial \boldsymbol{G}}{\partial y}=\boldsymbol{S} \tag{1}$$

$$\boldsymbol{q} = \begin{bmatrix} \mathrm{h} \\ q_x \\ q_y \\ hc \\ z_b \end{bmatrix}, \quad \boldsymbol{F} = \begin{bmatrix} q_x \\ uq_x + \dfrac{gh^2}{2} \\ uq_y \\ \dfrac{1}{\beta} q_x C \\ 0 \end{bmatrix}, \quad \boldsymbol{G} = \begin{bmatrix} q_y \\ vq_y + \dfrac{gh^2}{2} \\ vq_x \\ \dfrac{1}{\beta} q_y C \\ 0 \end{bmatrix}$$

$$\boldsymbol{S} = \begin{bmatrix} i \\ S_{bx} + S_{fx} \\ S_{by} + S_{fy} \\ E - D \\ \dfrac{D-E}{1-P} \end{bmatrix} = \begin{bmatrix} i \\ -gh\partial z_b / \partial x - C_f u\sqrt{u^2+v^2} - \dfrac{\rho_s - \rho_w}{2\rho} gh^2 \dfrac{\partial c}{\partial x} + \dfrac{\rho_s - \rho_w}{2\rho} \dfrac{u\partial z_b}{\partial t} (\dfrac{1-p}{\beta} - C) \\ -gh\partial z_b / \partial y - C_f v\sqrt{u^2+v^2} - \dfrac{\rho_s - \rho_w}{2\rho} gh^2 \dfrac{\partial c}{\partial x} + \dfrac{\rho_s - \rho_w}{2\rho} \dfrac{u\partial z_b}{\partial t} (\dfrac{1-p}{\beta} - C) \\ -\dfrac{q_b - q_{b*}}{L} \\ \dfrac{1}{1-p}\left[\alpha(\dfrac{q_b - q_{b*}}{L}) + (1-\alpha)(D-E)\right] \end{bmatrix}$$

where h is the flow depth, $\boldsymbol{q}$ represents the flow variable vector consisting of η; **F** and **G** are the flux vectors of the conserved variables in the x and y directions, respectively; **S** represents source vector; S_b represents bed slope in source terms; S_f represents friction in source terms; q_x and q_y are the *x* and *y* components of unit discharge q (m^2/s), respectively; i is the rainfall intensity (m/s); S is the flow direction in the coordinate system; n is Manning's friction coefficient; α_f is the angle between S and x, which can be determined by flow surface gradients in the x and y coordinates(◦); g is gravitational acceleration;

The sediment deposition rate D and the sediment stripping rate E can be calculated by the following formula, where κ and ζ the coefficient is 0 ~ 1:

$$\mathrm{D} = \kappa \omega_s C_a \tag{2}$$

$$\mathrm{E} = \zeta \omega_s C_{ae} \tag{3}$$

The calculation formulas of near-bed sediment concentration and near-bed sediment equilibrium concentration are as follows:

$$C_a = C \times \min(2.0, (1-p)/C) \tag{4}$$

$$C_{ae} = 0.00156 \frac{(\theta - \theta_{cr})}{\theta_{cr}} \left[1 + 0.0024 \frac{(\theta - \theta_{cr})}{\theta_{cr}} \right] \tag{5}$$

ω_s represents the sedimentation velocity of sediment particles.

2.2 Numerical solution

The finite volume method is used for the discretization of the control equation. The corresponding discrete formula obtained by integrating the governing equation (1) with the element (i, j) using Green theorem:

$$\int_\Omega \frac{\partial \mathbf{Q}}{\partial t} d\Omega + \int_\Omega \left(\frac{\partial \mathbf{F}}{\partial x} + \frac{\partial \mathbf{G}}{\partial y} \right) d\Omega = \int_\Omega \mathbf{S} d\Omega$$

$$\mathbf{q}_{i,j}^{n+1} = \mathbf{q}_{i,j}^{n} - \frac{\Delta t}{\Delta x}(\mathbf{F}_{i+1/2,j} - \mathbf{F}_{i-1/2,j}) - \frac{\Delta t}{\Delta y}(\mathbf{G}_{i,j+1/2} - \mathbf{G}_{i,j-1/2}) + \Delta t \mathbf{S}_{i,j} \tag{6}$$

Which, Δt time step (s); i, j unit serial number; Δx Represents the size of a rectangular grid in the x direction; Δy represents the size of the rectangular grid in y direction; $\mathrm{F}_{i-1/2,j}$ represents the flux of the rectangular grid interface (*i*−1/2, j); $\mathrm{F}_{i+1/2,j}$ represents the flux of the rectangular grid interface (*i*+1/2,j); $\mathbf{G}_{i,j-1/2}$ represents the flux of the rectangular grid interface(i, j−1/2); $\mathbf{G}_{i,j+1/2}$ represents the flux of the rectangular grid interface i, j+1/2); $\mathbf{S}_{i,j}$ Represents the source item of the cell (i, j) at the cell center.

In order to ensure the stability of the model, the single-parameter minmod limiter is used to limit the gradient, and the formula is as follows:

$$\phi_{(r_i)} = \max\left[0, \min(r_i, 1)\right] \tag{7}$$

$$r_i = \frac{f_+ - f_i}{f_i - f_-} \tag{8}$$

Where, i is rectangular Cartesian element; “+”represents upstream;“-”represents the downstream unit.

For the solution of the continuous equation and the discrete form of the momentum equation, this model uses the central upwind scheme to solve the flow and momentum flux on the unit interface, and combines with the linear reconstruction of the interface variable to make it have the second-order accuracy in space. Non-negative water depth reconstruction method is used to deal with dry-wet boundary problem; The flux calculation was solved by HLLC approximate Riemann solver; The slope source term can be converted into the algorithm calculation of the flux form of this unit interface; The bottom slope friction term is calculated by the proposed new implicit algorithm; Second-order explicit Runge-Kutta is used to update the values of flow and flux in time.

In order to ensure the stability of the explicit scheme in the calculation process, the appropriate time step is required. Courant-Friedrichs-Lewy (CFL) is applied to calculate the time step, and the calculation formula is as follows, the value range of

CFL is 0 ~ 1, and the value of CFL this paper.

$$\Delta t = CFL \min\left(\frac{R_i}{\sqrt{u_i^2 + v_i^2} + \sqrt{g h_i}}\right) \tag{9}$$

3. Results and discussion

3.1 Simulation of Soil Erosion under Different Vegetation Cover Patterns

As shown in **Fig.1**, a physical model of slope erosion under different vegetation coverage was established. Vegetation coverage is divided into A, B, C, D, E five cases, A for vegetation coverage is 0, B vegetation coverage is 30%, C vegetation coverage is 50%, D vegetation coverage is 70%, E vegetation coverage is 90%, in addition to the bare slope, the reason for choosing the above four vegetation coverage is that it is generally believed that the threshold coverage rate of vegetation affects about 50 % of soil erosion (Zhang et al.,2012). The length of the slope is 4 m, and the width is 1.5m. The slope of the slope is 12°, and the slope of the gully is 25°. The designed scouring flow is 5.2L·min^{-1}, which is also based on the existing research results and the actual rainfall intensity in the study area, equivalent to the rainfall intensity of moderate rain in the Loess Plateau. The model parameters are as follows: the density of water is 1000kg/m^3, the density of sediment particles is 2650kg/m^3, and the gravity acceleration is 9.8N/kg. Manning coefficient is set to 0.012 s/m$^{-1/3}$, soil porosity is set to 0.51, time step is adaptive time step, the total simulation time is 200s. In the whole simulation process, the coron number is 0.5. Since the soil water content was nearly saturated before the experiment, the infiltration value was assumed to be a stable infiltration rate of 34.8 mm/h in the numerical simulation process.

[Figure 1 goes here]

[Figure 2 goes here]

The volume of slope erosion is calculated as equation (10). Since each grid cannot be regular after slope erosion, the unit grid type after erosion can be divided into two cases, as shown in **Fig. 2**, case 1 and case 2. The total erosion volume of the whole slope can be obtained by integral summation of formula (12) and (13).

$$V_E = \sum H_i S \tag{10}$$

We are assumption:

$$\begin{aligned} & f(x,y) \quad o \\ & D: a \le x \le b; \varphi_1(x) \le y \le \varphi_2(x) \end{aligned} \tag{11}$$

Then there are:

$$\text{Case 1:} \iint_D f(x,y)\, d\delta \tag{12}$$

$$\text{Case 2:} \iint_D f(x,y)\, d\delta = \lim_{\lambda \to 0} \sum_{i=1}^{n} f(\xi_i, \eta_i) \Delta\delta_i \tag{13}$$

$$\begin{aligned} & \iint_D f(x,y)\, d\delta = \iint_D f(x,y)\, dxdy = \iint_D f(r\cos\theta, r\sin\theta)\, rdrd\theta \\ & x \to r\sin\theta; y \to r\cos\theta; dxdy \to rdrd\theta \end{aligned} \tag{14}$$

$$\begin{aligned} & \iint_D f(x,y)\, dxdy = \int_a^b dx \int_{\varphi 1(x)}^{\varphi 2(x)} f(x,y)\, dy \\ & \iint_D f(r\cos\theta, r\sin\theta)\, rdrd\theta = \int_\alpha^\beta d\theta \int_{\varphi 1(\theta)}^{\varphi 2(\theta)} f(r\cos\theta, r\sin\theta)\, dr \end{aligned} \tag{15}$$

Water above is an important factor affecting erosion and sediment transport on convex slopes.

As shown in **Fig. 2**, the erosion process of 0 ~ 18s is simulated by the model. At the beginning of the runoff, the surface water flow is a thin layer of water, which gathers down along the slope. On the one hand, this flow carries scattered particles, on the other hand, it peels off and transports the surface sediment. This erosion process is also the conversion process of energy consumption by the interaction between runoff drag force and soil shear force. Specifically, when t=2s, the slope flow began to form, after t=4 s, the erosion of the concentrated flow on the slope made the surface form grooves, with the advance of the erosion duration, when t=8 s, the lateral unevenness of the slope was gradually increased, the turbulence of the flow was intensified, and a relatively stable runoff channel was formed when t=11 s. Then, continue to scour along the road, the slope surface appears intermittent concave convex scour hole. In this case, the erosion force has changed from the initial flow shear force to the superposition force of flow shear force and gravity. In this case, the sudden particles on the slope are no longer single particles into suspension, but move in the form of bed load on the slope, and the intensity of erosion becomes more intense. The above process continues under the action of water flow, and the length of the rill is also increasing.

[Figure 3 goes here]

[Figure 4 goes here]

3.1.1 Calculation and correlation analysis of hydrodynamic characteristic parameters

Reynolds number is an dimensionless number, which is usually used to represent the flow pattern of water. With the increase of Reynolds number, the flow pattern of flow develops from laminar flow to turbulent flow. According to the formula of open channel flow, the critical value of laminar flow to turbulent flow is 500. The calculation formula of Reynolds number is as follows:

$$\mathrm{R}_e = \frac{u_{mean} h}{v_m} = \frac{q}{v_m}$$

v_m represents the kinematic viscosity of silt-laden water ($m^2.s^{-1}$), calculated as follows (Sha, 1965):

$$v_m = \frac{v}{1 - \frac{S_v}{2\sqrt{d_{50}}}}$$

$$v = \frac{0.01775}{1 + 0.0337t + 0.000221t^2}$$

v represents the kinematic viscosity of clear water ($m^2.s^{-1}$), t represents the flow temperature(°C), S_v represents the volumetric sediment concentration (%) and d_{50} is the median diameter of the sediment (mm).

The Froude number calculation formula is as follows:

$$F_r = \frac{u_{mean}}{\sqrt{gh}}$$

g represents the gravitational acceleration ($m.s^{-2}$).

Darcy--Weisbach friction is calculated as follows:

$$f = \frac{8ghJ}{u_{mean}^2}$$

Where J is the flume slope (mm^{-1}).

As show in **Fig .3**, the slope flow velocity decreased significantly with the increase of coverage ($P<0.01$). The law of exponential decline between velocity and vegetation coverage, the correlation is as follows:

$$y = 82.492e^{-1.327x}$$

$$R^2 = 0.9173$$

Analysis shows that the average runoff velocity of slope with vegetation cover is higher than that of bare slope The decrease of 35% indicates that vegetation coverage can significantly reduce slope flow velocity. When slope erosion occurs, it is necessary to overcome the resistance generated by vegetation, so the flow velocity will be reduced. With the increase of slope vegetation coverage area, the energy consumed by slope flow to overcome resistance is also larger, so the flow velocity is reduced. Vegetation coverage increased by 5%, and flow velocity decreased by about 5%~10%.Description of vegetation coverage The larger the slope, the more obvious the mitigation effect on the flow velocity. With the increase of vegetation coverage, the average resistance coefficient of slope flow exponential increase (**Fig.4**). With the increase of vegetation coverage, the water resistance area of vegetation increases correspondingly, which slows down the flow pattern, reduces the shear stress, and then reduces the flow velocity. The flow process of water flowing down through the vegetation also increases. The contact area between water flow and boundary increases, and the flow resistance increases. This study found that the slope resistance coefficient with vegetation coverage was 1.4~42 times that without vegetation coverage, and the average resistance coefficient range was 1.42~92.48. Some scholars have found that the drag-increasing effect of vegetation layout in strip pattern is significantly higher than that in strip, chessboard and random pattern. This is because the micro-topography formed by the close arrangement of plants is used as a new rough element to separate vortex, which consumes the runoff scouring energy twice. The vegetation coverage in this study was simulated by concentrated patch laying, and the maximum vegetation coverage was close to 100%. In other words, the higher the vegetation coverage, the gentler the water flow, the closer the flow pattern, the smaller the Froude number, the slower the flow velocity, the greater the dissipation of water energy, the greater the runoff resistance coefficient.

[Figure 5 goes here]

[Figure 6 goes here]

[Figure 7 goes here]

As show in **Fig.6** ,water flow shear stress increases first and then decreases with the increase of vegetation coverage, maximum shear force at about 60% coverage, the maximum runoff shear force is 4 pa, since then, runoff shear stress began to become unstable, ranging from about 4~7 pa. The reason may be that under the condition of consistent slope, runoff shear force is a function of runoff depth, combined with the interception and dispersion of vegetation coverage on runoff, the flow velocity decreases, the flow width of slope section with large vegetation coverage increases, the flow width of slope section without vegetation coverage decreases, the runoff depth increases, and the flow shear force increases gradually. And the greater the coverage, the stronger the interception, the greater the runoff depth, the greater the flow shear force.

As show in **Fig.7**, the unit flow power decreased with the increase of vegetation coverage, because with the increase of vegetation coverage, the blocking effect of vegetation on runoff gradually increased, the runoff velocity decreased, the kinetic energy decreased, and the unit flow power decreased. The runoff shear force, unit flow power and runoff kinetic energy increase with the increase of flow rate, because the greater the discharge flow, the greater the unit width flow, the greater the runoff depth, the greater the flow velocity, the greater the runoff kinetic energy and flow power.

[Figure 8 goes here]

[Figure 9 goes here]

3.1.2 Simulation and Evaluation of Runoff Velocity

Flow velocity is the most important hydrodynamic factor affecting sediment transport and soil erosion, as show in Fig.8, the flow velocity profiles under different vegetation coverages A, B, C, D and E were selected to compare the measured and simulated values, the variation range of flow velocity was as follows: 0.36~0.57m.s^{-1}, 0.22~0.46m.s^{-1}, 0.38~0.47m.s^{-1}, 0.33~0.46m.s^{-1}, 0.32~ 0.54m.s^{-1}. In the slope range, in the pattern A without vegetation coverage, the flow velocity showed a trend of increasing and then decreasing with fluctuation. In the channel range, the runoff velocity of pattern B and C is always at a low level, this indicates that the regulation range of vegetation coverage on runoff velocity may involve the whole slope, pattern B can well slow down the flow rate growth, and the flow rate to the bottom of the slope is only $0.241 m \cdot s^{-1}$, which can better regulate the sediment transport process within the range of the slope. Therefore, the mitigation effect of vegetation cover B on flow velocity is slightly weaker than that of vegetation cover C. Under the conditions of vegetation coverage D and E, the flow velocity in the channel is significantly higher than that of vegetation coverage B and C. This may be because the vegetation coverage is mainly on the upper part of the slope, and the bare slope below the coverage provides space for the increase in flow velocity and sediment erosion. In addition, it may be that the flow velocity of "clear water" is evenly distributed and larger than that of "muddy water", which eventually leads to an increase in the runoff velocity of D and E.

[Figure 10 goes here]

Usually, the four indicators were used to evaluate the simulation accuracy of the model, namely, relative deviation (RB), Nash coefficient (NSE), root mean square error (RMSE) and decisive coefficient (R^2), (16 ~ 19):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n_d}\left(M_i - S_i\right)^2}{N}} \tag{16}$$

$$R^2 = \frac{\left|\sum_{i=1}^{n_d}\left(M - \overline{M}\right)\left(S - \overline{S}\right)\right|^2}{\sum_{i=1}^{n_d}(M_i - \overline{M})^2 \sum_{i=1}^{n_d}(S_i - \overline{S})^2} \tag{17}$$

$$NSE = 1 - \frac{\sum_{i=1}^{n_d} (M_i - S_i)^2}{\sum_{i=1}^{n_d} (M_i - \overline{M})^2} \tag{18}$$

$$RB = 100 \frac{\sum_{i=1}^{n_d} (S_i - M_i)}{n\overline{M}} \tag{19}$$

NSE is an dimensionless goodness of fit index, ranging from negative infinity to 1. The NSE value of 1 indicates a perfect fit between the observed and simulated values.Under the background of watershed hydrological simulation, Moriasi et al. concluded that if RB is less than 15%, the model performance can be considered to be good. If NSE is equal to 1, the simulation results can be considered perfect. If NSE is between 0.75 and 1, it is very good. If NSE is between 0.65 and 0.75, it is very good. If NSE is between 0.5 and 0.65, it is satisfactory. If NSE is less than 0.5, it shows that the simulation results are not very good. The coefficient R^2 reflects the consistency between the simulated and observed values, The closer the value of R^2 is to 1, indicating that the simulation value and the observation value have high fitting degree. RMSE is 0, indicating that the simulated value and the observed value are perfectly fitted. If the RMSE value is less than half of the standard deviation of the observed value, the simulation effect of the model is good.

< Table 1 here please >

In order to compare the prediction accuracy of measured and simulated runoff velocity under different vegetation cover, the evaluation index of model simulation accuracy based on this paper (**Table 1**). From table 1, it can be seen that the RMSE of runoff flow velocity simulation values compared with the observed values is 0.39 ~ 0.65. Except for the case of vegetation cover E, the values of other vegetation cover simulation conditions are greater than 0.5. If NSE is between 0.5 and 0.65, it is satisfactory, indicating that the flow velocity of the model is reliable. Similarly, the variation range of R^2 is 63.84% ~ 87.89%, the closer the value is to 100%, indicating that the accuracy of the model is higher, except for vegetation cover B only 63.48%, the other values are above 75%; The variation range of RB is −0.01 ~ 0.02, and the variation range of RMSE is 0.01 ~ 0.11. The RMSE tends to be 0, indicating that the simulated value and the observed value are perfectly fitted. Through the analysis of the above four indicators, it is found that each value is better than the simulation results. It can be determined that the model proposed in this paper can well simulate the runoff velocity of slope erosion, which lays the foundation for the calculation of hydrodynamic parameters.

3.1.3 Analysis of cumulative erosion volume under different vegetation coverage

As show in **Fig.11**, erosion under different vegetation coverage conditions, all the sediment production processes fluctuate, and the variation of sediment production along different vegetation cover shows similar fluctuation trends and degrees. The cumulative erosion volume of vegetation cover A, B and C is significantly smaller than that of D and E. The reason is that vegetation cover B and C are above the channel and in the middle of the slope, which inhibits the growth of flow velocity and leads to the decrease of erosion capacity. Compared with no vegetation cover A (2636.27L), the amount of sediment eroded by vegetation cover B, C, D and E was 217.65L, 643.42L, 75L and 1929.368L respectively, the cumulative erosion volume is 5874.128L. This shows that under the condition of vegetation cover B and D, the effect of vegetation regulation on erosion has been weakened or even failed, or to some extent, increased runoff erosion. The erosion amount under vegetation coverage B and C was lower than that under bare slope, and the erosion amount under vegetation coverage B was 2418.96 L lower than that under bare slope. The erosion volume under vegetation coverage C decreased by 1993.204 L. The erosion volume under vegetation coverage C was stronger than that under vegetation coverage B, and the difference was about 425.25 L, under the condition of vegetation coverage C, the erosion amount decreased sharply. The erosion amount of beam slope and hill slope accounted for 30 % and 70 % respectively, and the erosion amount of each slope section in the slope range was low, indicating that the vegetation coverage at this time could well regulate the erosion and sediment transport process in the whole slope range.

In summary, no matter how the vegetation coverage pattern is arranged, even if the vegetation coverage has no obvious effect on erosion and sediment reduction under reasonable location conditions, it can generally slow down the erosion and reduce the erosion intensity. The results of this study showed that the extent and scope of action of the grass belt at position B and C to mitigate erosion were different. The regulation effect of vegetation cover B on erosion is slightly weaker than that of vegetation cover C.

[Figure 11 goes here]

Based on the above analysis, if vegetation covers the slope, the channel will be the main receiving part of the slope. If the vegetation cover position is on the upper slope, it will aggravate the erosion to a certain extent, causing the sediment yield to reach the peak; however, the vegetation slowing down the erosion position and the regulation range are different, the degree of erosion intensification and the main source of sediment also exist different. When the vegetation coverage is on the lower part of the slope, it will slow down the erosion, and the sand yield will be the lowest; but the scope of the slowed erosion is different, and the main part of the erosion will be different. If the vegetation coverage is at the bottom of the upslope, the scope for mitigating erosion is limited. In short, the primary function of vegetation cover is to inhibit the growth of flow velocity, thereby slowing down the erosion intensity of the entire slope and minimizing the amount of sediment production.

3.2 Erosion Simulation of Different Vegetation Coverage in Wangmaogou Watershed

Wangmaogou watershed ($110^{\circ}20'26'-110^{\circ}22'46'$E, $37^{\circ}34'13'-37^{\circ}36'03'$N) is located in Suide County, Shaanxi Province, China (**Fig. 10**). The basin area is about 5.97km^2, and the altitude varies from 935m to 1187.55m, it belongs to the first sub-region of loess hilly-gully region. The topography is typical loess landform, mainly hilly. Hydrological stations are located at the outlet of the basin. The region belongs to monsoon climate, and the annual average temperature and precipitation are 10.2°C and 513mm, respectively. More than 60 per cent of precipitation events are concentrated between July and September.

[Figure 12 goes here]

The watershed DEM is from 1:1000 topographic map, and its resolution is adjusted to 5m. **Fig.10** map rainfall from 4:40/26/07/2013 to 17:42/26/07/2013. Rainfall data and observed runoff data are from the Jiangkou hydrological station in Wangmaogou basin. In this paper, the erosion of different vegetation coverage in the basin is simulated to study the influence of different vegetation coverage on the erosion of the basin.

[Figure 13 goes here]

The change of erosion gully in the basin is affected by natural factors and human factors. Natural factors include climate, geological landform, surface material, vegetation and other factors. Human factors include the management of erosion gully and land, unreasonable utilization. This section discusses the impact of different vegetation coverage watershed erosion. The average elevations of inter-gully and valley in Wangmaogou watershed are 1085 m and 1040 m, respectively. The average elevation near the gully is 1070m, which is between inter- gully and valley. The average slope values of inter-gully land and valley land were 26° and 45°, respectively, and the average slope value near the gully was 35°. Based on the 5m resolution DEM data and rainfall data of Wangmaogou watershed, the proposed model was simulated for 2000 s, as shown in **Fig.12 ~ Fig.16**. Soil separation is the main source of sediment in the initial stage of erosion, and its activity can characterize the intensity of slope soil erosion.

[Figure 14 goes here]

[Figure 15 goes here]

[Figure 16 goes here]

[Figure 17 goes here]

[Figure 18 goes here]

We divided the vegetation coverage into four cases: 5%, 15%, 30%, 50%. We simulated the spatial distribution of erosion and velocity vector size distribution at each time of T=100 s ~ 1000 s, which can be used to qualitatively analyze the changes of erosion and deposition in the basin. As shown in **Fig.12**, when T= 0 ~ 100 s, with the beginning of rainfall duration, different vegetation coverage conditions show different laws. The vegetation coverage is 5%, and the spatial distribution of erosion is more obvious than that of other vegetation coverage. The vegetation coverage is 50 %, and the spatial distribution of watershed erosion is the smallest. That is to say, in the process of natural precipitation, if the rainfall intensity does not exceed the infiltration degree, the slope does not start runoff.

When T=200 s, when the vegetation coverage was 5 %, there was a significant erosion on the slope surface, and the velocity vector distribution was also obvious.

There were more branches to be eroded. When the vegetation coverage was 15 %, there were also obvious erosion branches, and the number was less than that of 5 % vegetation coverage. When vegetation coverage increased to 30 % and 50 %, erosion decreased from 5 % and 15 %. As the rainfall continued to T=300 s ~ T=500 s, it was found from the analysis of velocity vector diagram that the eroded branch ditches under various vegetation coverage gradually developed to a single branch ditch, indicating that the retrogressive erosion of slope surface began to develop to gully erosion. The above phenomenon shows that the surface runoff begins to scour the surface soil in the form of diffuse flow after the surface runoff is produced. In the process of runoff flowing from the slope to the channel, the flow velocity increases gradually due to the influence of surface fluctuation, forming a stream. Under the stream erosion, the slope erosion and sediment production begin to converge to the channel, and then the sediment transport occurs.

[Figure 19 goes here]

In particular, when T=1000 s, only a single channel appears after slope erosion, and the length of the erosion channel is longer than that of the previous period and the connectivity is better. It is preliminarily believed that the sediment transport to the channel is gradually silted after slope erosion, and the sediment-containing water is gradually transported to the outlet of the downstream channel. As shown in **Fig.17**, when T=3000 s, compared with T=1000 s, the development of slope gully is relatively stable, and the erosion and sediment yield on the slope have been transported to the gully to maintain a basically stable state.

To sum up, in the erosion process of soil on each slope of the basin under different vegetation coverage conditions, the overall trend of fluctuation increases with the extension of erosion time, and the deposition occurs from the slope erosion to the channel transport. When T=3000 s, it is basically stable. In horizontal comparison, the higher the vegetation coverage of the basin is, the less the sediment deposited in the gully is, and vice versa, indicating that the sediment transport amount of slope erosion is closely related to the dynamic change process of vegetation coverage of the basin. The larger the vegetation coverage is, the stronger the soil resistance is, the more the dynamic change of soil erosion rate tends to zero, and the development of erosion gully is inhibited to a certain extent. As shown in **Fig. 17**(A), the large variation density of erosion ditches is concentrated in the middle and lower reaches of the gully region. For **Fig.17** (D), part of the bare land is transformed to gardens and woodlands, and the forest and grassland gradually reach a certain degree of coverage. When the vegetation coverage increases to 50 %, it can effectively achieve runoff storage, and the quantitative water conservation benefits of vegetation begin to play a role.

4. CONCLUSIONS

The GAST model was used to simulate the runoff velocity under different vegetation coverage on the slope, and it was found that the simulated value was very consistent with the observed value. The simulation results were evaluated by combining the four indexes RMSE, R^2, NSE and RB, and the results were 0.39 ~ 0.87, 63.48 ~ 87.89,-0.01 ~ 0.02, 0.03 ~ 0.11, respectively. The results show that the proposed model can simulate slope erosion under different vegetation coverage, and the effect is better.

Different vegetation coverage and its spatial distribution have great influence on the hydrological runoff process of slope and watershed (channel). With the increase of vegetation coverage, the average velocity of slope and watershed (channel) decreased, the Darcy-Weisbach friction increased, and the unit runoff power decreased. The relationship between these parameters was logarithmic function and exponential function. It shows that the increase of vegetation coverage greatly inhibits the surface runoff velocity, increases the surface roughness and reduces the Fr value.

The relationship between soil erosion on slope and watershed and vegetation coverage and its types is very complex. In this paper, only the proposed GAST model is used to discuss the erosion of different vegetation coverage under slope and watershed conditions. In the future, the influence of vegetation height and underground root distribution should be considered comprehensively, and the comprehensive study of various vegetation factors needs to be further deepened.

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