Considering the Quantitative Effect of Antecedent Rainfall on Slope Stability to Predicting Rainfall-induced Shallow Landslides at the Basin Scale

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In this study, a new predicting models that can considering the quantitative effect of antecedent rainfall on shallow landslide for shallow landslides prone area predicting at the basin scale. The hillslope hydrology model is used to construct the relationship of antecedent rainfall to the height of ground water, the infinite slope stability theory is used to construct the relationship of antecedent rainfall to slope stability. At last, the model was applied at a basin area. Comparisons are made between considered and unconsidered antecedent rainfall. The results show that in the basin area, the shallow landslides prone area for considered the antecedent rainfall is larger than that unconsidered the antecedent rainfall. It is can be concluded that the antecedent rainfall is quite important and should not be ignored in shallow landslide hazard assessment.

Key words: shallow landslide, antecedent rainfall, slope stability, hillslope hydrology, infinite slope stability theory

1. INTRODUCTION

In mountainous areas, landslides are a common geological phenomenon and often result in a major financial losses, and even to a major human life losses. Landslides are triggered by many external environmental factors among which rainfall is the most significant one. Much data indicate that in the rainy season of China, the main and common type of rainfall-induced landslide are shallow landslides (*Wei et al*., 2006; *Guo et al*., 2005; *Li et al*., 1999; *Liu*, 1996). Generally, this phenomenon is main caused by extreme intense rainfall or intermittent rainfalls of medium intensity rainfall events. In previous studies of landslide-rainfall relationship, many researches focused on the intensities and durations of rainfalls and get the proper understanding. Caine (1980) is the first one using the empirical approaches to constructing the limiting threshold of rainfall intensity and duration for shallow landslide. Meanwhile, other researches (*Ono et al*., 2014; *Jemec*, 2013; *Guzzetti et al*., 2007; *Tsai*, 2006; *Chen et al*., 2006; *Aleotti*, 2004; *Brand et al*., 1984) also using the same method to explored the relationship of rainfall intensity and duration between shallow landslide. Another researchers using the physically-based model approaches which considering the physical features of slopes including local topographic, geologic and soil parameters as well as rainfall intensity and duration using to analysis the stability of shallow landslide (*Luo*, 2015; 2014; *Chang and Chiang*, 2009; *Rosso et al*., 2006; *Casadei et al*., 2003; *Borga et al*., 2002, 1998; *Wu and Sidle*, 1995; *Montgomery and Dietrich*, 1994). Here, Rosso et al. (2006) developed a physically-based model which considered some key characteristics of the soil mantle and both rainfall intensity and duration into the physical-based model to predict rainfall-induced shallow landslides. But, those researches seldom considered the antecedent rainfall.

Of course, some researchers have been aware of the significance of antecedent rainfall on rainfall-induced landslide. Glade (2000) using an empirical ‘‘Antecedent Daily Rainfall Model’’ which is a combination of rainfall occurring in a period before the event (antecedent rainfall) and rainfall on the day of the event to calculate the regional landslide-triggering rainfall thresholds for three and slide-prone regions in the North Island of New Zealand. Khan (2012) using the historical rainfall-landslide data of Chittagong City, Bangladesh to analyse the critical rainfall condition of the landslide events by Gumbel’s extreme value distribution. And then using the antecedent rainfalls to do the Gumbel’s distribution of the critical rainfall intensity–durations of each historical landslide. Guo (2013) take 23 debris flow events in Jiangjia Ravine as the study objects, found an I-D (Intensity-Duration) threshold of rain for debris flow by considering the antecedent rainfall. But, From these existing references, we found that almost all the studies are based on the empirical approach. This method have the advantage of simplicity using, but it considered the physics feature of hillside slopes as a 'black box' and overlooks the actually physical processes of landslide triggered by rainfall.

In this paper, according to the physical mechanics of rainfall-induced shallow landslide, a physically based model considered the antecedent rainfall is presented. This model using the Rosso's model of rainfall versus ground water table as the base, considered antecedent rainfall to construct the hillslope hydrology, and then combined with the infinite slope stability theory to explore the quantitative effects of antecedent rainfall on shallow landslide occurrence. At last, the model is apply in the Baisha river basin of Chengdu, Sichuan, China and the comparisons are made with the results from unconsidered the antecedent rainfalls.

2. HILLSLOPE HYDROLOGY MODEL AND SLOPE STABILITY MODEL

2.1 Hillslope hydrology model

This study is aim to explore quantitative effects of antecedent rainfall on shallow landslide. So we should construct the hillslope hydrology model first. The hillslope hydrology is consists of two mathematical parts (equations), one is used to describe the rainfall induce the ground water raising, and the other is used to describe the ground water recession after the rainfall stop. In this study, the expressions for ground water raising using the one's presented by Rosso et al. (2006). And the expressions for ground water recession is derived in this study.

2.1.1The expressions for ground water raising

In Rosso's model (2006), the expressions to describe rainfall induce the ground water raising is used widely (*Luo et al*., 2015; 2014). The expressions for ground water raising presented by Rosso et al (2006) is derived by coupling the conservation of mass of soil water with the Darcy's law and some assumptions:(1) overland water flow is generated by saturation excess; (2) the impermeable layer is shallow. And then, using the intersection of contour and flow tube boundaries orthogonal to the contours to define the topographic elements and a hillslope will be consisted by those topographic elements; (3) null soil volumetric strain and above the ground water table soil saturation degree of constant average; (4) rainfall is constant between time. So, Rosso et al (2016) obtained the equations for rainfall induce the ground water raising and which is shown as follows.

$$h=\frac{apz}{Tb\sin\theta}[1-\exp(-\frac{1+e}{e-es_r}\frac{Tb\sin\theta}{az}t)] + h_0\exp(-\frac{1+e}{e-es_r}\frac{Tb\sin\theta}{az}t), \quad for\frac{ap}{Tb\sin\theta}>1 \tag{1}$$

where, p is the net rainfall, a is the upslope contributing area, b is the width of the topographic elements, h is the height of the ground water table, θ is the slope angle to the horizontal, s_r is the average degree of saturation, e is the average void ratio above the groundwater table, K is the saturated conductivity of the soil, t is the rainfall duration time, T is the hydraulic transmissivity, with $T = Kz$, z is the thickness of the landslide, h_0 is the initial height of ground water table before it rains.

2.1.2 The expressions for ground water recession

Rosso et al (2006) presented the expressions for ground water raising in exp. (1). From the expression (1), we can see that there has an initial condition should be given. The initial condition is the height of ground water table before it rains. So, in this study, the initial height of ground water table h_0 is using to considering the quantitative effects of antecedent rainfall on groundwater. That is to say, if we know how high does the ground water table generated by antecedent rainfall when it is rain, the quantitative effects of antecedent rainfall can be solve out.

As we all know, after rain stop, the ground water table will be lowered by seepage flow, evaporation and other ways. Thus, the expressions for ground water recession should be derived to determine there has how much ground water generated by antecedent rainfall was left before this rains happen.

In order to building the expressions of ground water recession, some additional assumptions had been made as follow:

(1) The ground water table lowered only by seepage flow.

(2) After the groundwater table lowered the soil water content should be return to the initial water content.

Then, based on the assumptions and the principle of water balance (seepage flow discharge equate to the reduced groundwater), we can establish the following expression.

$$q=\frac{ds}{dt}=-a\frac{e}{1+e}(1-S_r)\frac{dh}{dt} \tag{2}$$

where q is the seepage flow discharge, and the other parameters are as before.

Here, using the Darcy's law provides the seepage flow in the groundwater table. We can obtained,

$$q = bhK\sin\theta \qquad (3)$$

And then, substituting the expression (3) into expression (2) yields

$$bhK\sin\theta = -a\frac{e}{1+e}(1-S_r)\frac{dh}{dt} \qquad (4)$$

By solve the equation (4), we can obtained

$$h = h_a \exp\left(-\frac{1+e}{e-es_r}\frac{Tb\sin\theta}{az}t\right) \qquad (5)$$

where h_a is the height of groundwater table at the time of the antecedent rainfall stop, and the other parameters are as before. Here, h_a can be obtained by using expression (1) for set h_0 =0. It should be note that before the antecedent rainfall happen, we can considering the simple case of no groundwater in a hillslope .

By solve expression (5), the height of groundwater table varies with the time can be obtained. And a simple case is using here to illustrate the process of ground water recession after rainfall stop. And the results obtained by using the expression (5) is shown is **Fig. 2**. All the parameters using here are also shown in **Fig. 2**. From the **Fig. 1**, we can see that the groundwater table become lower and lower after rain stop. At the twelfth day after rain stop, the height of groundwater table is about $0.001h_a$. For this example the landslide thickness assume as 1m, that is means at this time the height of ground water is less than 1mm ($h_a \leq z$) which almost could be ignored. That is to say if the interval between rainfalls is larger than twelve days, the effect of the antecedent rainfall could not be take into account.

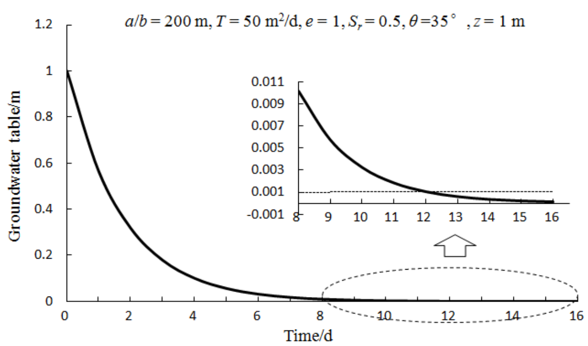

Fig. 1 Height of the groundwater table versus time after rain stop

Thus, Equation (1) and (5) compose the hillslope hydrology model. By the hillslope hydrology model presented in this study, the quantitative effect of antecedent rainfall on groundwater table can be take into account and calculated. Here, we take a simple case to illustrate this process. We assume that the antecedent rainfall is stop 3 days before this rain, and lasted 4 day (**Fig. 2**). Before the antecedent rainfall, there is no rain occurred. By using the hillslope hydrology model presented in this study, we can calculate the variation of groundwater table in this process and the results shows as follow.

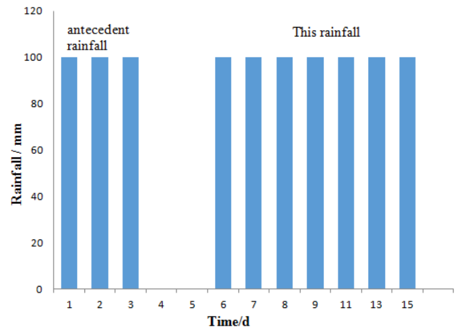

Fig. 2. The distribution of antecedent rainfall and this rain

Fig. 3 shows the height of the groundwater table versus rainfall duration considered and unconsidered the antecedent rainfall. It shows that before the antecedent rainfall occurring, the height of groundwater table is 0. When the antecedent rainfall happen the groundwater table begin to rising, and then reducing by rain stop till the second rainfall come. Here, at the beginning of the second rainfall, there has an initial height of groundwater table which is generated by the antecedent rainfall. This is the quantitative effects caused by the antecedent rainfall. By comparison to the results that unconsidered the antecedent rainfall, we can see the initial height of groundwater table is assumed as 0, and the height of groundwater table is lower than results that obtained by considered the antecedent rainfall. The antecedent rainfall has the strong effect on the groundwater table.

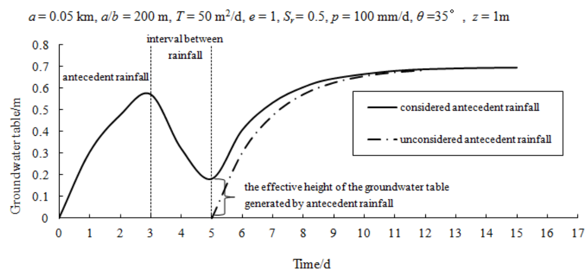

Fig. 3. Comparison of height of the groundwater table versus rainfall duration considered and unconsidered antecedent rainfall

In the simple case, only once antecedent rainfall is taken into account in our hillslope hydrology model. It should be note that no matter how many times antecedent rainfall occurred, we can using the model in this study by put the effective height of groundwater table generated by the previous rainfall as the initial height of the groundwater table for the latter rainfall, and so on. The effect of all the antecedent rainfall on the groundwater table can be taken into account.

2.2 Slope stability model

Many data indicated that rainfall-induced shallow landslides are often sliding along the interface between soil and rock. In mountainous, the surface of the slope is often parallel to the interface between soil and rock. So, for a hilly area the depth of rainfall-induced shallow landslide is small if compared with the length of the shallow landslide. As we all know, if the thickness of a sliding mass on a slope is much smaller than the slope's length, the infinite slope assumption can be used to calculate the safety factor of the slope by analysis of a rigid wedge or rigid slice of material of unit width and unit thickness.

A rigid slice with unit width and unit thickness is chosen to calculate the safety factor for a slope as shown in **Fig. 4**.

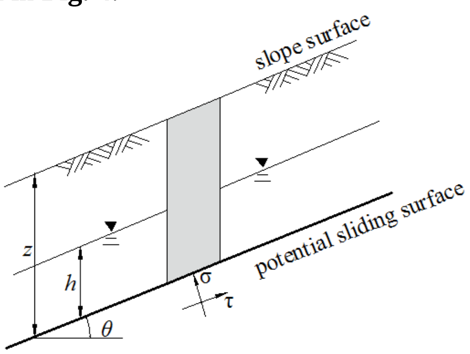

Fig. 4. Computed model for slope stability analysis

Based on the Mohr-Coulomb theory, the shear stress of the soil along the potential failure plane τ_f can be expressed as follow

$$\tau_f = c + (\sigma - u)\tan\varphi \tag{6}$$

where, c is the cohesion of the soil, σ is the normal total stress, u is the pore water pressure, and φ is the internal friction angle of the soil.

If we use the τ_s to denote the shear stress, the safety factor can be written as follows.

$$F_s = \frac{\tau_f}{\tau_s} \tag{7}$$

Here, the expressions for total stress σ, u, and τ_s are

$$\sigma = [(z-h)\gamma + hr_{sat}]\cos^2\theta \tag{8}$$

$$u = hr_w \cos^2\theta \tag{9}$$

$$\tau_s = [(z-h)\gamma + h\gamma_{sat}]\cos\theta\sin\theta \tag{10}$$

where γ is the average unit weight of the soil, γ_{sat} is the saturated unit weight of the soil, and γ_w is the unit weight of water, z is the depth of the shallow landslide.

Then, with the assumption that the slice is rigid and by substituting expressions (8)-(10) and (6) into Equation (7), the expression for the safety factor of a slope can be obtained as the following.

$$F_s = \frac{c + [(z-h)\gamma + h\gamma']\cos^2\theta\tan\varphi}{[(z-h)\gamma + h\gamma_{sat}]\sin\theta\cos\theta} \tag{11}$$

Based on the results as shown in **Fig. 3**, the results of the safety factor versus rainfall duration considered and unconsidered the antecedent rainfall as shown in **Fig. 5**. From **Fig.5** we can see that the safety factor varies with the height of groundwater table. *Fs*=1 is the limiting equilibrium condition of slope stability (*Chang*, 2009; *Rosso*, 2006; *Tasi*, 2006; *Montgomery*, 1994). At the time of the antecedent rainfall stop, the safety factor is larger than 1. That is to say the slope is stable at that time. And then subsequent rainfall caused the slope failure. By comparisons between considered and unconsidered the antecedent rainfall, we can see that the slope failure may occur at the eighth day which is the rainfall lasted 3 days by considered the antecedent rainfall. And if unconsidered the antecedent rainfall, the slope failure may happen at the ninth day which is the rainfall last 4 days. That is to say for the rainfall lasted 3 days, the slope will become unstable by considered the antecedent rainfall, and remain stable by unconsidered the antecedent rainfall. It is demonstrate that the antecedent rainfall effect on the shallow landslide should not be ignored.

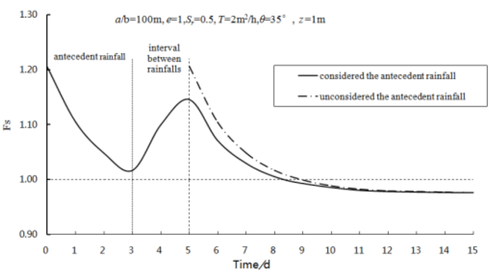

Fig. 5. Comparison of safety factor versus rainfall duration considered and unconsidered the antecedent rainfall

3. APPLICATION AND DISCUSSION

3.1Study area

Baisha river basin of Dujiangya city is chosen as the study area to mapping prone areas of rainfall-induced shallow landslides from the application of the model presented in this study. Meanwhile, comparisons are made with the results unconsidered the antecedent rainfall. Baisha river basin is located in Dujiangyan. Dujiangyan is on the west side of Chengdu city in Sichuan Province, China. Baisha river basin is high in north-west, and low in south-east. Based on the geological data of Dujiangyan, the Lithological formations in Bashahe river basin can be divide as three major groups. They are pyrolith and metamorphic rock, carbonate and clastics in carbonate rock, carbargillite in sand and mud interbeded rock. Rainfall is abundant in Baisha river basin, the mean annual average precipitation is 1134.8mm. And the rainfall occur main in May to September every year. Thus, many landslide occur in Baisha river basin at those months. From the rainfall-induced landslide data of the Chengdu Land Resources Bureau, we found that rainfall-induced landslide in Baisha river basin are main in shallow landslide, and the depth of the shallow landslide is generally about 1m. Thus, the soil depth is assumed to 1m in our application.

In order to mapping the prone areas of rainfall-induced shallow landslides from the model and make comparisons to unconsidered the antecedent rainfall, the precipitation is assumed to 100mm/d in Baisha river basin, and antecedent rainfall is assumed to happen before 4 day and lasted 3 days with the precipitation is 100mm/d too. That is to say, the interval between rainfalls is 1 day. Before the antecedent rainfall there is no rain happen. Digital elevation data with 25×25m grid resolution were used. The soil parameters of the three major lithological formations used in this study is given in **Table 1**. The soil parameters is obtained by soil sample tests and consulting geological survey data and a handbook of engineering geology.

Table 1. Input soil parameters

Lithological unit	γ (kN/m^3)	T (m^2/d)	c' (kPa)	φ'(°)
Pyrolith and metamorphic rock	21	55	3.5	40
Carbonate and clastic in carbonate rock	19.6	80	3.0	38
Carbargillite in sand and mud interbeded rock	17.6	60	2.6	33

3.2 Results

Based on the hillslope hydrology model presented in this study, distribution of the effective height of groundwater table generated by the antecedent rainfall in Baisha river basin is obtained, as shown in **Fig.6**. From the **Fig.6**, the effective height of groundwater table generated by the antecedent rainfall in Baisha river basin is main in 0-0.1m, only a few areas has the effective groundwater table height in the range of 0.1-0.409m. The maximum height of groundwater table generated by the antecedent rainfall in Baisha river basin is 0.409m. And then, the distribution of groundwater table height which is considered the antecedent rainfall in Baisha river basin at rainfall duration t=1d is shown in **Fig. 7**. From **Fig. 7**, we can see that the maximum height of groundwater table is 0.994m. By comparison to the results of unconsidered antecedent rainfall, at the same area the height of the groundwater table of considered antecedent rainfall is larger than the one's unconsidered antecedent rainfall. And the maximum height of groundwater table in Baisha river basin for unconsidered antecedent rainfall is 0.924m. Therefore, the effect of antecedent rainfall on groundwater table is obviously. It is thus the antecedent rainfall should be take part in the hillslope hydrology analysis.

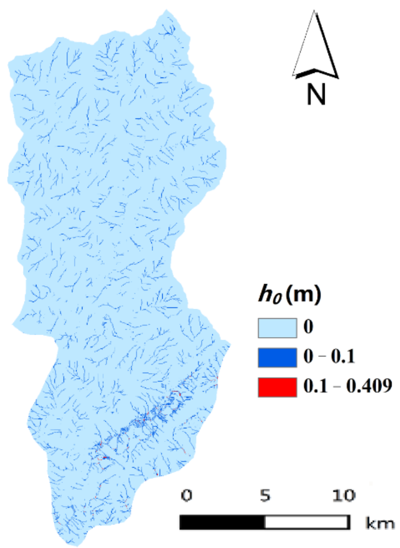

Fig. 6 Distribution of the effective height of groundwater generated by the antecedent rainfall in Baisha river basin

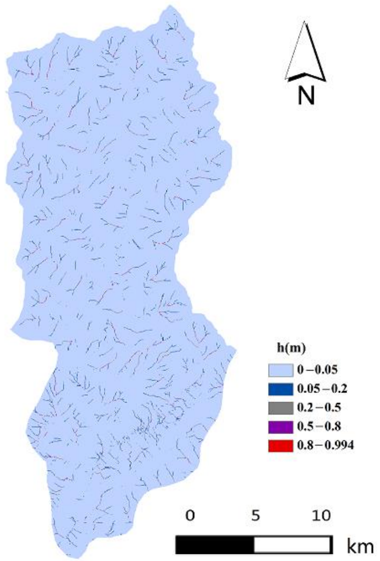

Fig. 7 Distribution of the height of groundwater table considered antecedent rainfall in Baisha river basin at rainfall duration t=1d

Based on the distribution of the groundwater table height h obtained by considered the antecedent rainfall, using the slope stability model, the results of unstable shallow landslide regions in Baisha river basin at the rainfall durations t=1d can be obtained and which is shown in **Fig. 8**. Furthermore, in order to show the difference of shallow landsliding prone areas in Baisha river basin between considered antecedent rainfall and unconsidered antecedent rainfall, a table of unstable topographic cells percentage for rainfall durations t=1d obtained by considered and unconsidered antecedent rainfall is worked out, and shown in table 2.

Fig. 8 is a map of Baisha river basin showing unstable shallow landslide region by overlap the unstable shallow landslide area distribution between considered and unconsidered antecedent rainfall at the rainfall duration of 1d. It shows that unstable rainfall-induced shallow landslide are widely distributed in Baisha river basin. The shallow

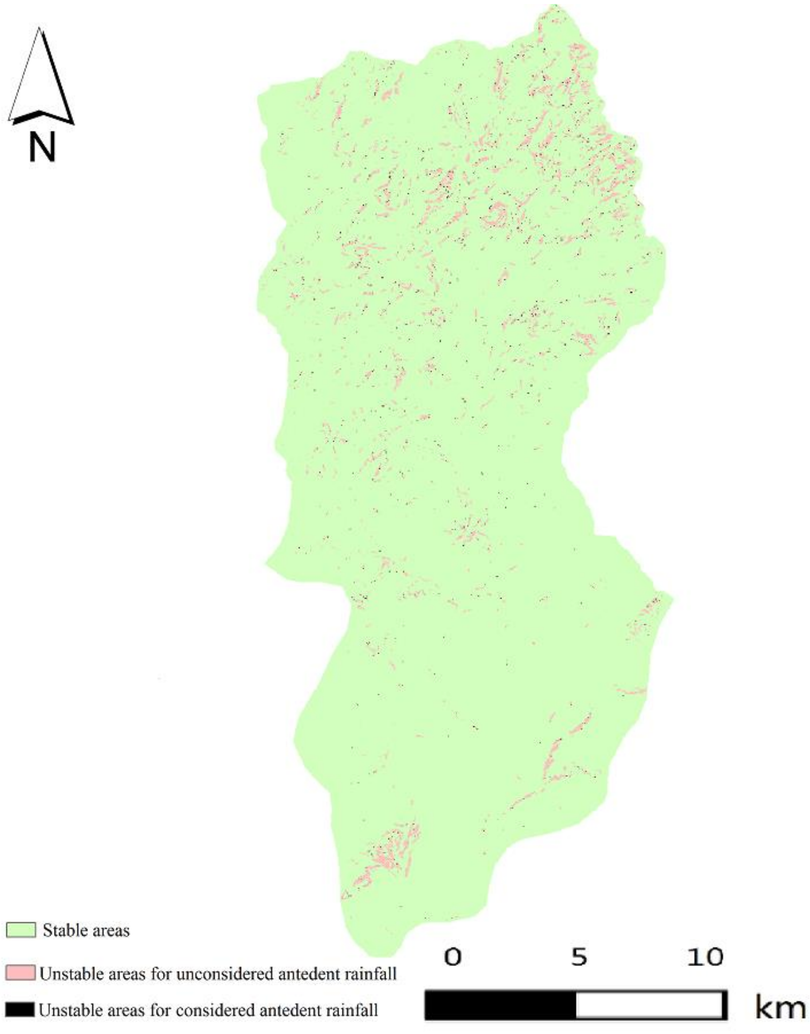

Fig. 8. Comparison of the unstable shallow landslide areas in Baisha river between considered and unconsidered antecedent rainfall

landslide prone areas of considered the antecedent. rainfall is more than the one's unconsidered the antecedent rainfall.

Table 2 shows the percentage of unstable topographic elements for the different rainfall durations obtained by the two different conditions. It shows that the percentages of unstable topographic elements obtained by considered and unconsidered the antecedent rainfall are 4.08% and 3.88% respectively. that is to say the unstable topographic elements by considered the antecedent rainfall in Baisha river basin are more than unconsidered the antecedent rainfall. Although, the difference are only 0.2%, but we known the area of Baisha river basin is 363km^2.This means that the 0.2% difference represents a different unstable topographic cells area of 726000m^2. Therefore, we have demonstrated that the antecedent rainfall has an obvious effect on shallow landslides. It is quite important to consider the effect of antecedent rainfall in mapping the hydrologic controlled shallow landslide prone area predicting.

Table 2. Percentage of unstable topographic cells for rainfall durations t=1d obtained by considered and unconsidered antecedent rainfall.

Conditions	Considered antecedent rainfall	Unconsidered antecedent rainfall
Total area of unstable cells	4.08%	3.88%

4. CONCLUSIONS

A physically-based model considered the antecedent rainfall, which is an improvement from the pioneering model presented by Rosso et al. (2006), was developed in this study and is used to mapping the rainfall-induced shallow landslide prone area in Baisha river basin. The model combined hydrologic and topographic control on shallow landslides, adding the effect of antecedent rainfall on shallow landslide by an additional expression to describe the ground water recession to improve the hillslope hydrology model and considered the quantitative effect of antecedent rainfall on the slope stability to improve the shallow landslide stability analysis. This paper used simple examples and applied in study area to illustrate the method. Lastly, comparisons are made between considered and unconsidered the antecedent rainfall to demonstrate the rationality of the model of this study.

The main conclusions of the study follow.

(1) The quantitative effect of antecedent rainfall on groundwater table can be take into account by an additional initial height of groundwater table. By comparisons, the height of groundwater table of unconsidered the antecedent rainfall is lower than results of considered. The antecedent rainfall has the strong effect on the groundwater table.

(2) For a same slope, the results of the stability analysis may be different for considered or unconsidered the antecedent rainfall. That is to say, the slope may be stable by unconsidered the antecedent rainfall and unstable by considered the antecedent rainfall. It is demonstrated that the antecedent rainfall effect on the shallow landslide should not be ignored.

(3) Application is made in Baisha river basin, the results showed that antecedent rainfall has an obvious effect on shallow landslides. The percentage of unstable topographic cells obtained by considered the antecedent rainfall is larger than that unconsidered. That is, some parts of stable elements become unstable by considered the effect of antecedent rainfall. Antecedent rainfall has strongly effect on rainfall-induced shallow landslide predicting.

(4) The study show that considered the antecedent rainfall in mapping the hydrologic controlled shallow landslide prone area predicting and landslide hazard assessment are quite important. The model presented in this study provided a new approach to solve the problem of the quantitative effects of antecedent rainfall on shallow landslide in rainfall-induced landslide predicting and hazard assessment. It is hope to improve the accuracy of results of rainfall-induced landslide hazard assessment and found useful for regional landslide forecast.

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