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METHODOLOGY **Open Access**

# A physical model considered the effect of overland water flow on rainfall-induced shallow landslides

Yu Luo[1], Si-ming He[1,2*], Fang-zhu Chen[3], Xin-po Li[1] and Jin-chuan He[4]

## Abstract

**Background:** It is well know that many shallow landslides are triggered by rainfalls. In previous studies of shallow landslide models, the effect of overland water flow on slope stability was ignored.

**Results:** In this paper, a physical model considered the effect of overland water flow on rainfall-induced shallow landslides is derived and applied to predict the landslides. The slope stability model is developed by considering the depth of overland water flow in infinite slope stability theory. Hillslope hydrology is modelled by coupling the overland uniform water flow equation with Rosso's seepage flow equation. And then, the model is used to assess the slope stability in Dujiangyan of China, and the results is compare with Rosso's model.

**Conclusions:** This model is simple, but has the capability of taking into account the effect of overland water flow in the triggering mechanism of shallow landslide. The results of case study show that the overland water flow can make an obvious effect on shallow landslides, so it is quite important to consider the overland water flow in shallow landslide hazard assessment.

**Keywords:** Shallow landslide; Rainfall; Overland water flow; Slope stability; Hillslope hydrology

## Background

Landslides are one of the most serious geological hazards in mountainous areas. External environmental factors, such as rainfall, earthquakes and human activities, may all result in landslides. Much data indicate that about 90% of landslides are triggered by rainfall or related to rain (Li et al. 2004; Xu et al. 2005; Liu et al. 2007). In China, many landslides occur in the rainy season, but the main and common type of landslide is the shallow landslides (Wei et al. 2006; Liu 1996; Li et al. 1999; Guo et al. 2005).

Research on rainfall-induced landslides, especially shallow landslides, has been a favourite topic for researchers. These researchers have the goal of developing a more reasonable landslide model to predict rainfall-induced landslides in order to reduce loss of human life and property. Currently, two approaches are commonly used: empirical approaches and physical-based model.

Empirical approaches using rainfall events that triggering and non-triggering landslides to develop an expression of rainfall threshold for landslide occurrence (Campbell 1975; Caine 1980; Brand et al. 1984; Aleotti 2004; Chen 2006; Guzzetti et al. 2007). Empirical approaches have the advantage of simplicity using in the landslide hazard assessment, but it overlooks the actually physical processes of the landslides triggered by rainfall.

Physical-based model approaches are developed by considering the physical features of slopes including local topographic, geologic and soil parameters as well as triggering rainfall conditions, such as rainfall intensity and duration, related to landslide stability. For shallow landslide, various physical-based models have been obtained using assumptions of steady or dynamic hydrological conditions.

Using the assumption of a steady or quasi-steady water table and groundwater flows parallel to the hillslope, and by coupling with infinite slope stability analysis, many physical-based models have been built (Montgomery and Dietrich 1994; Wu and Sidle 1995; Borga et al. 1998, 2002; Casadei et al. 2003; Rosso et al. 2006; Chang and

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* Correspondence: hsm@imde.ac.cn
[1]Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu 610041, China
[2]Center for excellence in Tibetan plateau earth sciences, China academy of sciences, Beijing 100101, China
Full list of author information is available at the end of the article

Chiang 2009). Montgomery and Dietrich (1994) developed a simple physical-based model for predicting the shallow landslide. This model is developed by coupling local topographic data with hydrological modelling and the infinite slope stability models. The model is then applied to shallow landslide hazard assessment with the aid of GIS technology. Subsequently, Rosso et al. (2006) developed a physical-based modelling for hydrologic control of shallow landslides. This model takes into account both rainfall intensity and duration in building a hillslope hydrologic model. Then, it couples the hillslope hydrologic model with the infinite slope stability model to build a rainfall threshold model. The stability model includes some key characteristics of the soil mantle. Once developed, this physical-based model is applied to the prediction of rainfall-induced shallow landslides.

However, the physical model presented by Rosso et al. (2006) does not consider the effect of overland water flow. In model application, the unconditionally stable slopes is defined as if the ground water table rose to the slope surface with the safety factor even greater than 1. In this consideration, the effect of overland water flow is ignored. Whether so-called unconditionally stable slopes can still remain stable under overland water flow quires further study.

By the assumptions of unsteady flow, other researchers have used both Richard's equation and the Green-Ampt infiltration model, combined with a slope stability model, to predict shallow landslides triggered by rainfall (Gasmo et al. 2000; Iverson 2000; Cho & Lee 2002; Kim et al. 2004; Tsai & Yang 2006). These models were able to provide insights into the physical process of shallow landslides triggered by rainfall, but they have some complex parameterization and are difficult to apply in landslide hazard assessment in some areas. They also do not consider the effect of overland water flow on slope stability.

Based on the physical-based model presented by Rosso et al. (2006), the present paper considers the effect of overland flow on shallow landslide stability and presents a new model for mapping areas prone to rainfall-induced shallow landslides. The slope stability model accounts for the depth of overland water flow in infinite slope stability theory. The hillslope hydrology model includes equations add to describe the overland water flow with the assumption of uniform flow. Finally, this model is applied in Dujiangyan, China, and the comparisons are made with the model presented by Rosso et al. (2006).

## Method

### Hillslope hydrology

In this study, treatment of hillslope hydrology consists of two mathematical parts (equations), one is used to describe the seepage flow and the other is used to describe the overland water flow. The equation for seepage flow using in this study is the one presented by Rosso et al. (2006). The equation for overland water flow is derived based on the assumption of an uniform overland water flow.

#### *The equation of seepage flow*

The hillslope hydrology model presented by Rosso et al. (2006) established the equation that is used in this study to describe the seepage flow as a part of the model. Rosso's seepage flow equation is derived by coupling the conservation of mass of soil water with the Darcy's law. Here, the seepage flow equation is established using the assumptions that overland water flow is generated by saturation excess, subsurface flow is parallel to the slope surface, and the impermeable layer is shallow. Using topographic elements to divide the hillslope, as shown in Figure 1, the topographic elements are defined by the intersection of contour and flow tube boundaries orthogonal to the contours, and the equation of seepage flow is as follows.

As shown in Figure 1, $p$ denotes the net rainfall, $z$ denotes the thickness of the landslide, $a$ is the upslope contributing area, $b$ is the width of the topographic elements, and $h$ is the height of the subsurface flow. By water balance and Darcy's law, the following expression can be obtained

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

where $\theta$ 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, and the other parameters are the same as in the previous.

Based on Equation (1) for the initial condition of stable piezometric condition at the depth of $h\ (0) = h_0$, we obtain

$$\begin{aligned} h = {} & \frac{apz}{Tb\sin\theta}\left[1-\exp\left(-\frac{1+e}{e-es_r}\,\frac{Tb\sin\theta}{az}t\right)\right] \\ & + h_0\exp\left(-\frac{1+e}{e-es_r}\,\frac{Tb\sin\theta}{az}t,\right) \quad for\,\frac{ap}{Tb\sin\theta} > 1 \end{aligned} \tag{2}$$

For the simple case of $h_0 = 0$, the height of the subsurface flow is expressed as follows:

$$h = \left\{ \begin{array}{cc} \dfrac{apz}{Tb\sin\theta}\left[1-\exp\left(-\dfrac{1+e}{e-es_r}\dfrac{Tb\sin\theta}{az}t\right)\right], & t \le t^* \\ z, & t > t^* \end{array} \right\} \tag{3}$$

and

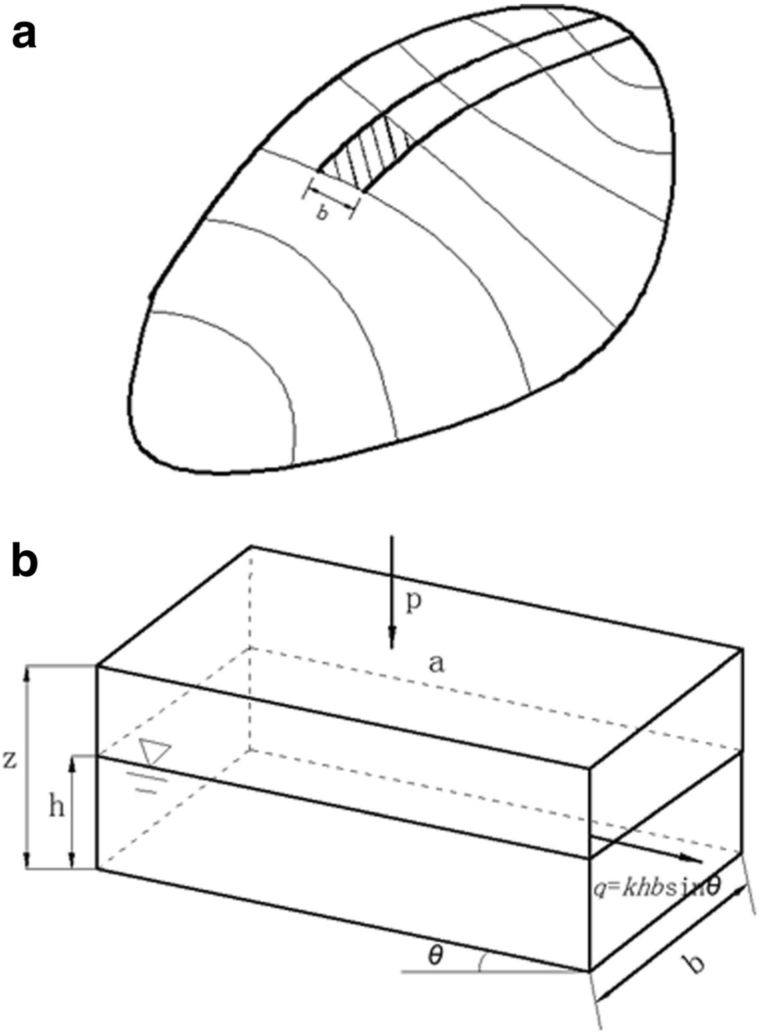

**Figure 1 Hydrological model of shallow slope. (a)** Planar view of grid map. **(b)** Underwater fluxes.

$$t^* = -\frac{e-es_r}{1+e}\frac{za}{Tb\sin\theta}\ln\left(1-\frac{Tb\sin\theta}{ap}\right) \tag{4}$$

where $T$ is the hydraulic transmissivity, with $T = Kz$, here, and $t^*$ is the time of the ground water table rising up to the slope surface.

### *Equation of overland flow*

In Rosso's hillslope hydrology model, overland water flow is generated by saturation excess. That is to say, when the ground water rises up to the slope surface and rainfall continues, overland water flow is generated. Nevertheless, in Rosso's hillslope hydrology model, no equation is given to describe overland water flow. Thus, an equation of overland flow should be derived to improve the hillslope hydrology model.

In order to obtain the equations for the relationship between overland water flow and rainfall, the following assumptions were made:

1) No erosion occurs on the slope surface.
2) The overland water flow is uniform flow, which means that streamlines are parallel with each other. That is to say, the overland flow is parallel to the slope surface.

Then, based on the assumptions and the principle of water balance, we obtain the following expression:

$$ap-q-r = a\frac{dl}{dt} \tag{5}$$

where, $q$ is the seepage flow discharge, by Darcy's law $q = bzK\sin\theta$, $r$ is the discharge of the overland flow, $l$ is the depth of the overland flow, and the other parameters are as before.

Here, the overland water flow is assumed to be an uniform flow. So, based on the hydraulics, the overland water flow can be written as

$$r = vbl \tag{6}$$

where, $v$ is the average velocity of overland flow, $l$ is the depth of the overland water flow, and the other parameters as the same as in the previous.

Then, substituting Equation (6) into Equation (5) yields

$$ap - bzK\sin\theta - vbl = a\frac{dl}{dt} \tag{7}$$

The Chezy formula provides the average velocity in uniform flow. Thus, we have

$$v = C\sqrt{RJ} = C\sqrt{l\sin\theta} \tag{8}$$

where,the Chezy coefficient C can be given by the Manning formula,

$$C = \frac{1}{n} l^{1/6} \tag{9}$$

Where $n$ is the roughness coefficient.

Then, substituting Equations (8) and (9) into Equation (7) yields

$$ap - bzK\sin\theta - \frac{1}{n} bl^{5/3}(\sin\theta)^{1/2} = a\,\frac{dl}{dt} \tag{10}$$

The finite difference method can be used to solve Equation (10), and Equation (10) can be discretized as follows.

$$\mathrm{ap}\Delta\mathrm{t} - bzK\sin\theta\Delta t - \frac{1}{n} bl(t)^{5/3}(\sin\theta)^{1/2}\Delta t = a\,[l(t+1) - l(t)] \tag{11}$$

By solving Equation (11), the depth of overland water flow with different rainfall and time can be obtained.

Thus, Equations (3) and (10) compose the hillslope hydrology model. By the hillslope hydrology model of this study, groundwater height or the depth of overland water flow can be obtained at any time, and the processes of groundwater rising and overland water flow being generated can be calculated. Here, we take a simple case to illustrate this process. We choose the thickness of a landslide as 1 m and use the other parameters shown in Figures 2 and 3.

Figure 2 shows the relations of $h + l$ against rainfall intensity. For a given slope, $h + l$ increase with increasing duration of rainfall. The larger rainfall intensity, the faster the $h + l$ increase rate, and the earlier the time for overland water flow generation, resulting in higher overland water flow depth.

In order to analyse the relationship of overland water flow depth with rainfall intensity, the overland water flow in Figure 3 is scaled up in Figure 2. Here, it should be noted that time begin with the groundwater table rising to the slope surface, that is overland water flow is beginning to be generated. In Figure 3, the time for overland water flow to begin to generate $t^*$ is given for different rainfall intensities. The figure shows that the larger the rainfall intensity, the higher the overland flow depth. The depth of overland water flow increases with increase rainfall duration time and then becomes nearly constant. Here, the depth of overland water flow is quite

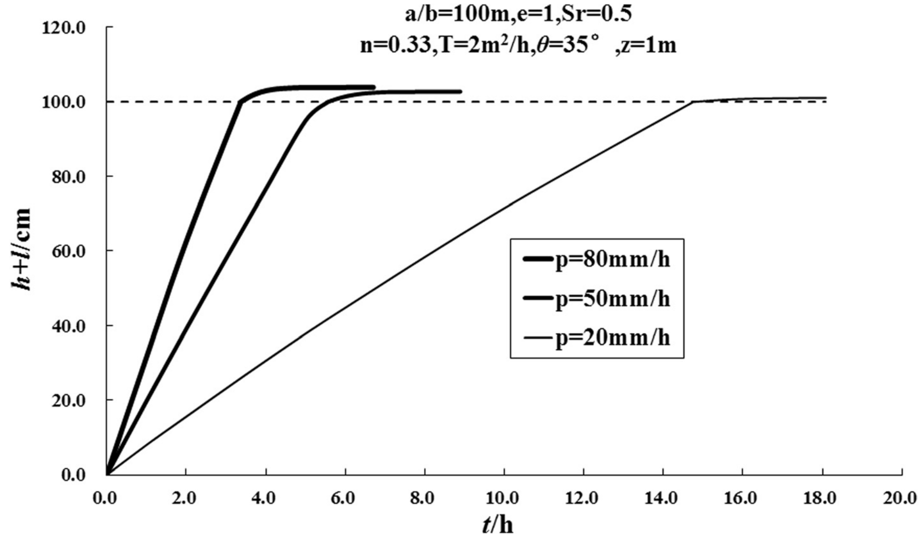

**Figure 2** **Variability of subsurface flow and overland flow versus rainfall duration for different rainfall intensities.**

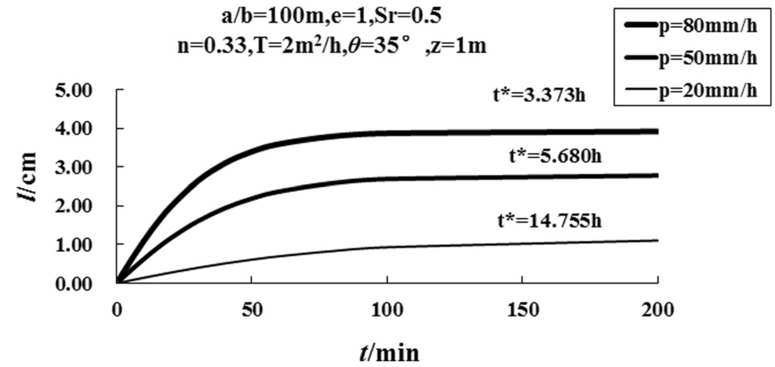

**Figure 3 Height of overland flow versus rainfall duration for different rainfall intensities.**

small, several centimeters or millimeters, and the result is in accordance with the actual case.

## Slope stability

In traditional analysis of slope stability, overland water flow is not taken into account. As is well known, the depth of overland water flow is only several centimeters or millimeters, which may have little effect on a stable slope with a large safety factor; however, for a slope in the limiting equilibrium condition, the effect of overland water flow should not be ignored. This is because the overland water flow with only several centimeters or millimeters may cause the so-called stable slope to become an unstable slope. Especially, in landslide hazard assessment, not considering the effect of overland water flow may result in an incorrect assessment and lead to serious damage in the so-called safety area, which is obtained by landslide hazard assessment without consideration of the effect of overland water flow on the stability. Thus, in order to avoid the aforementioned accidents, the effect of overland water flow should be taken into account in slope stability analysis.

As we all know, if the thickness of a sliding mass on a slope is much smaller than the slope's length, the slope can be called an infinite slope. For an infinite slope, edge effects can be neglected in stability analysis. That is to say, the safety factor of the slope can be determined by analysis of a rigid wedge or rigid slice of material of unit width and unit thickness. Here, in an area scale, the thickness of the landslide is much smaller than the length. Thus, the infinite slope assumption can be used in this study.

In Figure 4, a rigid slice with unit width and unit thickness is chosen to evaluate the safety factor for a slope. The depth of overland water flow is shown by $l$, the depth of the slope is $z$, the height of the subsurface flow is $h$, and $\tau_w$ is the shear stress of the overland water flow acting on the slope. Overland water flow may add to the pore pressure and the flow motion causes a shear stress acting on the slope. These are both disadvantages for slope stability.

On the basis of the Mohr-Coulomb theory, the shear stress is expressed as

$$\tau_f = c + (\sigma - u)\tan\phi \tag{12}$$

where, $\tau_f$ is the shear strength of the soil, $c$ is the cohesion of the soil, $\sigma$ is the normal total stress, $u$ is the pore water pressure,and $\phi$ is the internal friction angle of the soil.

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

$$F_s = \frac{\tau_f}{\tau_s} \tag{13}$$

Here, the expressions for total stress $\sigma$, $u$, and $\tau_s$ are

$$\sigma = \begin{cases} [(z-h)\gamma + hr_{sat}]\cos^2\theta, & h\leq z \\ zr_{sat}\cos^2\theta + \gamma_w l\cos^2\theta, & l\geq 0 \end{cases} \tag{14}$$

$$u = \begin{cases} hr_w\cos^2\theta, & h\leq z \\ (z+l)r_w\cos^2\theta, & l\geq 0 \end{cases} \tag{15}$$

$$\tau_s = \begin{cases} [(z-h)\gamma + h\gamma_{sat}]\cos\theta\sin\theta, & h\leq z \\ z\gamma_{sat}\cos\theta\sin\theta + \gamma_w l\cos\theta\sin\theta + \tau_w, & l\geq 0 \end{cases} \tag{16}$$

where $\gamma$ is the average unit weight of the soil, $\gamma_{sat}$ is the saturated unit weight of the soil, and $\gamma_w$ is the unit weight of water.

In Equation (16), the shear stress of the overland water flow acting on the slope $\tau_w$ can be derived by using hydraulics, as follows,

$$\tau_w = \gamma_w RJ = \gamma_w l\sin\theta \tag{17}$$

Then, with the assumption that the slice is rigid and by substituting Equations (14)-(16) into Equations (12) and (13), the expression for the safety factor of a slope can be obtained as the following.

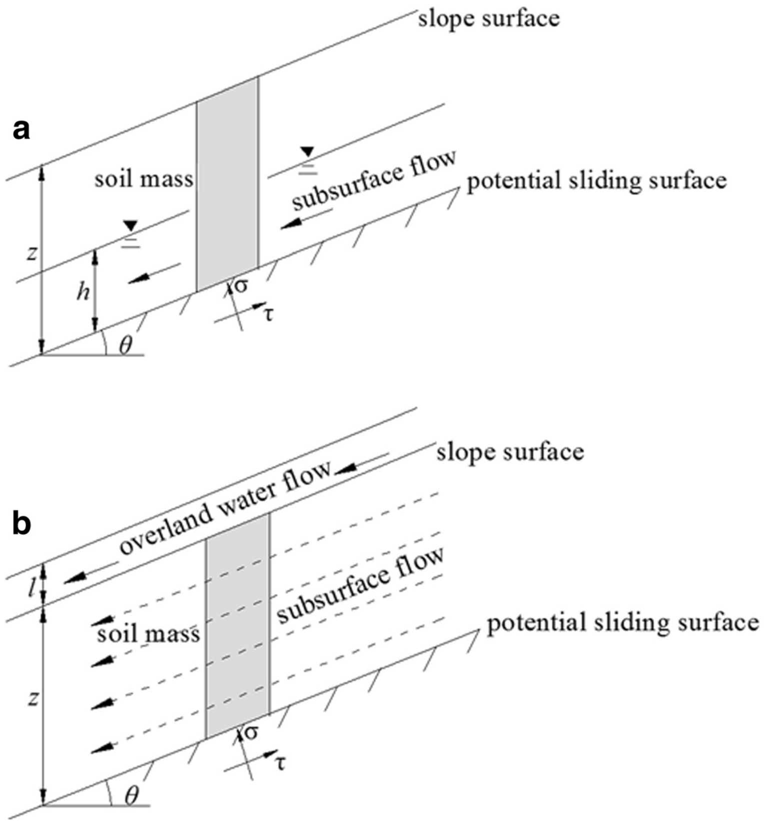

**Figure 4 Computed model for slope stability analysis: (a) $h \le z$, (b) $l > 0$.**

$$F_s = \frac{c + \left[(z - h)\gamma + h\gamma'\right]\cos^2\theta \tan\phi}{\left[(z - h)\gamma + h\gamma_{sat}\right]\sin\theta\cos\theta + \gamma_w l\cos\theta\sin\theta + \gamma_w l\sin\theta} \tag{18}$$

Figure 5 shows the variability of the safety factor $F_s$ at different rainfall intensities. For a given slope, $F_s$ decreases with increasing of rainfall duration time, and the rate of decrease of $F_s$ becomes faster for larger rainfall intensity. Additionally, in Figure 5, the $F_s$ for $h = z$ and $Fs = 1$ is shown. $Fs = 1$ is the limiting equilibrium condition of slope stability (Montgomery and Dietrich 1994; Rosso et al. 2006; Tsai and Yang 2006; Chang and Chiang 2009). Thus, the figure shows that when the groundwater table rises to the slope surface, the safety factor is larger than 1 for each rainfall intensity. That is the slope is stable. However, with continuing rainfall, overland water flow is generated and the safety factor decreases continuously until the depth of overland water flow remains constant. The figure shows that the safety factor decreases to values smaller than 1 for each rainfall intensity under overland water flow, i.e. the slope is now unstable.

In the existing research, if the ground water rises up to the slope surface, and the slope safety factor $F_s \ge 1$, thus the slope is unconditionally stable for shallow landslide hazard assessment (Rosso et al. 2006; Chang and Chiang 2009). However, from Figure 5, we see that overland water flow causes the stable slope to become unstable. Hence, the "unconditionally stable" slope is not unconditionally stable. Considering the influence of overland water flow is quite important for shallow landslide hazard assessment.

## Results and discussion

### Study area

Dujiangyang, the study area, is located on the west side of Chengdu city in Sichuan Province, China. The Dujiangyan region, with an area of 1208 km$^2$, regularly experiences landslides triggered by rainfall, especially in Hongkou, Longchi, and the scenic spot Qingcheng Mountain (Figure 6).

There are four major lithological formations in Dujiangyan city. They are pyrolith and metamorphic rock, carbonate and clastics in carbonate rock, carbargillite in sand and mud interbeded rock, loose sedimentary rock. By soil sample tests, and by consulting geological survey data and a handbook of engineering geology, the soil parameters of the four major lithological formations are given in Table 1. It should be noted that the roughness coefficient $n$ in the study area is 0.035, which was

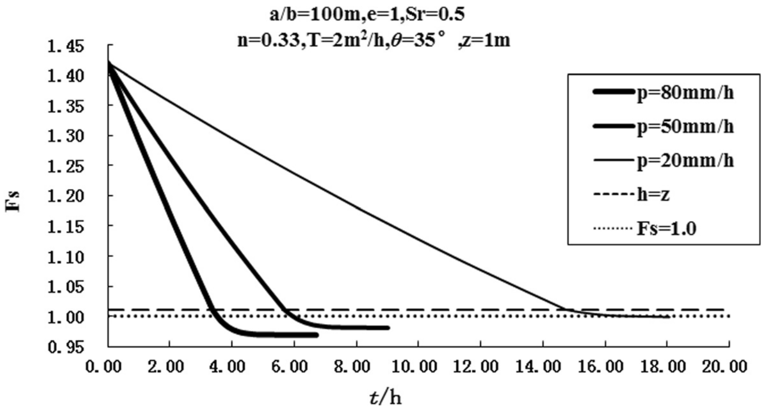

**Figure 5** Variability of safety factor versus rainfall duration for different rainfall intensities.

chosen from the Hydraulics (2001) of overland water flow on the grass land.

Rainfall-induced landslide data of the Chengdu Land Resources Bureau show that the depth of rainfall-induced landslide in Dujiangyan is generally about 1 m. Thus, in this study, the soil depth in the Dujiangyan study area is assumed to 1 m. Here, it is assumed that the initial groundwater height $h_0 = 0$. The rainfall distribution of Dujiangyan, digitized from the yearly maximum hourly rainfall distribution in Sichuan Province, is shows in Figure 7. Digital elevation data with 25 × 25 m grid resolution were used. Lastly, the results obtained by

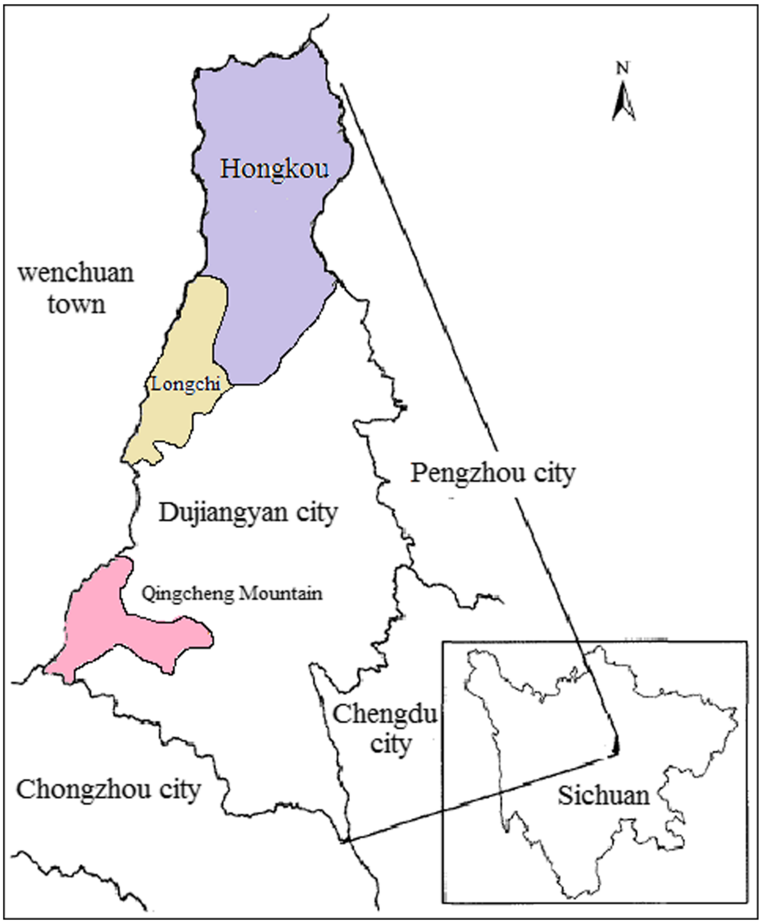

**Figure 6** Location of Dujiangyan city.

**Table 1 Input soil parameters**

| Lithological unit | $\gamma$ (kN/m$^3$) | $T$ (m$^2$/d) | $c'$(kPa) | $\varphi'$(°) |
|---|---|---|---|---|
| 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 |
| Loose sedimentary rock | 16.6 | 130 | 0 | 34 |

this approach were compared with the results obtained by Rosso et al. (2006).

## Results

The hillslope hydrology model was applied to predict the variation of groundwater height and overland water flow depth in Dujiangyan under rainfall. Rainfall durations of 0.3, 0.6, 1.2 and 1.8 h were chosen for the analysis. Through the analysis, the maximum values of $h+l$ in Dujiangyan at the different rainfall durations are 0.272, 0.55, 1.0034 and 1.025 m for the 0.3, 0.6, 1.2 and 1.8 h durations, respectively. Distribution of $h+l$ in Dujiangyan at the rainfall durations of 0.6 and 1.8 h are shown in Figure 8. For a maximum value of $h+l$ is less than 1, that is, the groundwater table is under the slope surface, no overland water flow is generated in Dujiangyan. For a maximum value of $h+l$ larger than 1, overland water flow is generated, and the depth of the overland water flow is $(h+l)$-1. For example, from Figure 8, the maximum depth of overland flow is 2.5 cm at the rainfall duration of 1.8 h. It can be concluded that when the rainfall duration is 0.3, 0.6 h, no overland flow is generated; however, when the rainfall duration is 1.2 or 1.8 h, overland water flow is generated in some parts of Dujiangyan.

Based on the distribution of $h+l$ in Dujiangyan, and using the slope stability model, the unstable shallow landslide region under rainfall can be worked out. In order to analyse the distribution of unstable shallow landslide region in Dujiangyan at different rainfall durations, the rainfall durations of 0.3, 0.6, 1.2 and 1.8 h were also chosen for analysis. Furthermore, in order to show the effect of overland water flow for predicting rainfall-

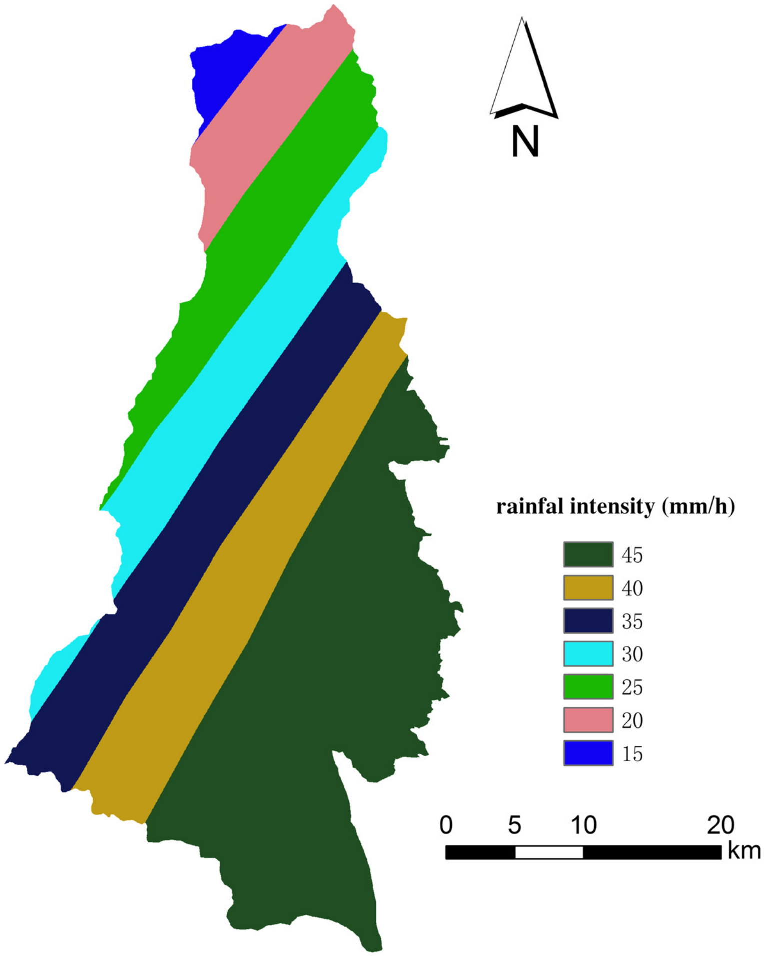

**Figure 7** The distribution of the rainfall intensity in Dujiangyan.

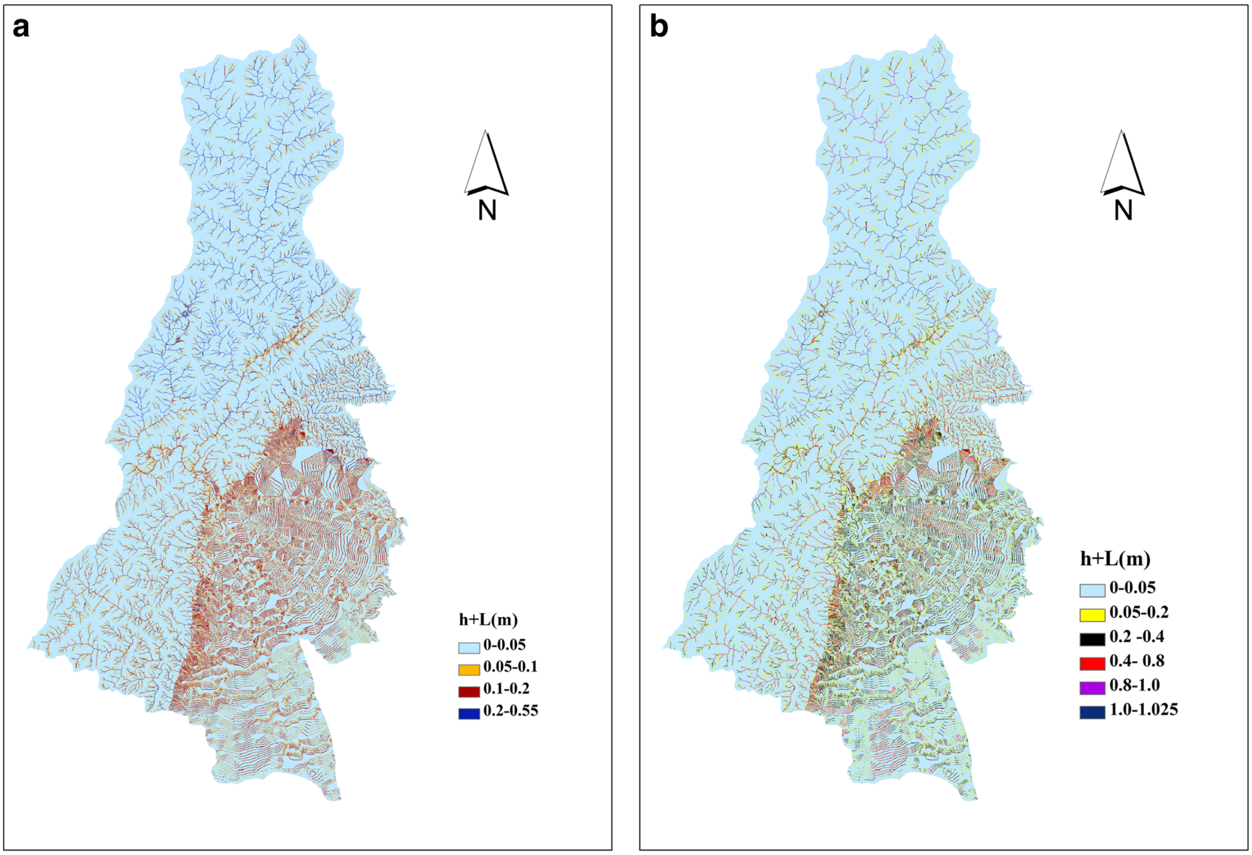

**Figure 8** Distribution of *h* + *l* in Dujiangyan at different rainfall durations: (a) 0.6 h, (b) 1.8 h.

induced shallow landslides, a comparison is made with the Rosso-Rulli-Vannucchi model (2006).

Figure 9 is a map of Dujiangyan showing unstable shallow landslide region at the rainfall duration of 1.8 h. It shows that unstable rainfall-induced shallow landslide areas are mainly in Hongkou, Longchi and the scenic spot of Qingcheng Mountain, which is similar to the existing landslide investigation in Dujiangyan.

Table 2 shows the percentage of unstable topographic elements for the different rainfall durations obtained by the two different models. It shows that the unstable topographic elements increase with increasing rainfall duration, and thus that rainfall-induced shallow landslides also increase with increasing rainfall duration. The percentages of unstable topographic elements obtained by the model of this study are larger than those obtained by the Rosso-Rulli-Vannucchi model. From Table 2, we can see that the difference between the model of this study and Rosso-Rulli-Vannucchi model is only about 0.01%, but the area of Dujiangyan city is 1208 km$^2$. This means that the 0.01% difference represents a different unstable topographic cells area of 120800 m$^2$. Therefore, we have demonstrated that overland water flow has an obvious effect on shallow landslides. It is thus important to consider the effect of overland water flow in landslide hazard assessment.

## Conclusions

A physical-based model considering the effect of overland water flow, which is an improvement from the pioneering model presented by Rosso et al. (2006), was developed in this study and is used to predict rainfall-induced shallow landslides. The model preserves the model presented by Rosso et al. (2006) in explaining the combined hydrologic and topographic control on shallow landslides. Moreover, it includes an additional the equation to describe overland water flow to improve the hillslope hydrology model and considers the effect of overland water flow on the slope stability to better analyse the slope stability. Here, the equation of overland water flow was derived by the assumption that overland water flow is uniform flow. The effect of overland water flow on slope stability is accounted for by the additional pore pressure that results the shear stress acting on the slope. We used simple examples and applied in study area to illustrate the method. Lastly, we

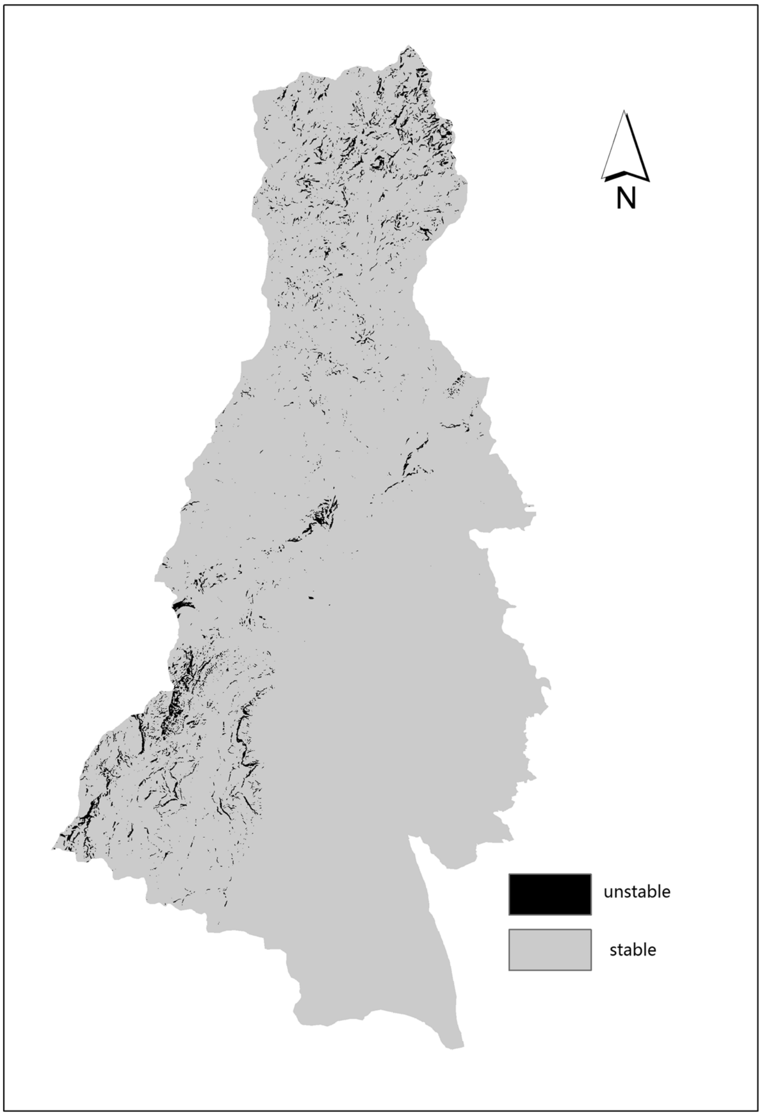

**Figure 9** Map of Dujiangyan showing unstable shallow landslide areas at the rainfall duration of 1.8 h.

made comparisons with the Rosso-Rulli-Vannucchi model to demonstrate the rationality of the model of this study model.

The main conclusion of the study follow.

(1) The depth of overland water flow is higher at larger rainfall intensity, and this depth increases with increasing rainfall duration time until it finally becomes constant. Additionally, the depth of overland water flow is quite small, only several centimeters or millimeters, which is in accordance with the actual case.

(2) Overland flow can decrease the safety factor of the slope. For a so-called unconditionally stable slope (Fs > 1 with groundwater table up to the slope surface), overland water flow may lead to an

**Table 2 Percentage of unstable topographic cells for different rainfall durations obtained by two different models**

| Rainfall duration/hours | | No overland flow | | Overland flow generated | |
|---|---|---|---|---|---|
| | | **0.3** | **0.6** | **1.2** | **1.8** |
| Total area of unstable cells | This study model | 2.69% | 2.70% | 2.72% | 2.74% |
| | Rosso-Rull-Vanucchi model | 2.69% | 2.70% | 2.71% | 2.73% |

unstable condition. That is, the “unconditionally stable” slope is not unconditionally stable.

(3) The results obtained by applying the model of this study to the study area showed that overland water flow has an obvious effect on shallow landslides. Overland water flow is generated in some parts of Dujiangyan under the rainfall conditions. The percentage of unstable topographic cells obtained by the model of this study is larger than that obtained by the Rosso-Rulli-Vannucchi model. That is, some parts of stable elements become unstable by the effect of overland flow.

(4) The study showed that overland water flow should be considered in rainfall-induced shallow landslide assessment. Using this model in rainfall-induced landslide hazard assessment will hopefully improve the accuracy of results and be found useful for regional landslide prediction.

**Competing interests**

The authors declare that they have no competing financial interests.

**Authors’ contributions**

YL, XL, and JH participated in the field investigations; YL and SH designed the research schemes and theoretical analysis. FC and JH obtained the parameters for calculation, and YL drafted the manuscript. All authors read and approved the final manuscript.

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**Author details**

[1]Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu 610041, China. [2]Center for excellence in Tibetan plateau earth sciences, China academy of sciences, Beijing 100101, China. [3]College of Water Conservancy and civil Engineering, South China Agricultural University, Wushan road, Tianhe, Guangzhou 510642, China. [4]Southwest Municipal Engineering Design & Research Institute of China, Chengdu 610081, China.

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