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# The impact of physiographic factors upon the probability of slides occurrence: a case study from the Kaoping River Basin, Taiwan

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## ABSTRACT

This study has investigated the influence of physiographic factors upon the probability of slide occurrence in the Kaoping River Basin. According to previous literature, statistical tests, and physical mechanisms, three physiographic factors (slope steepness, the dip slope ratio, and the time-dependent landslide ratio) were significantly related to slide occurrence. These were combined with hydrological factors (cumulative rainfall) to establish an assessment model for estimating the probability of slide occurrence using logistic regression. The model's overall accuracy in the training and validation stages was about 81%. Overall, 20 randomly selected historical rainfall events were employed for verification, including 10 events each with and without slide occurrence. The results showed that the model accuracy was approximately 80%, if the probability threshold  $P_{sh}$  is set to be 0.5.

This assessment model can assist in prediction of slide occurrence and the proposed subsequent engineering measures or vegetation restoration is often able to reduce the landslide ratio and the probability of slide occurrence. After landform changes, the model's physiographic factors can be updated to adjust the rainfall threshold for slide occurrence. Given an appropriate cumulative rainfall and an acceptable risk of slide occurrence, the model can identify priority regions for slide prevention.

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Physiographic factors; the landslide ratio; logistic regression; probability of slide occurrence; nonparametric statistical test

## 1. Introduction

Slides and debris flows are the most common natural disasters on the mountain slopes of Taiwan. Slides directly cause loss of lives and property, and the flow of sediment into riverbeds provides the source material for debris flow. The mechanisms underlying the occurrence of slides include intrinsic and extrinsic factors. Intrinsic factors include the area's slope steepness, elevation, the dip slope ratio, the landslide ratio, geological conditions, and other physiographic factors. Extrinsic factors include water, earthquakes, volcanic activity, and other triggering mechanisms, of which water saturation is the most crucial factor (Highland and Bobrowsky 2008). This study has investigated the influence of physiographic factors on the occurrence of slides. The following were the main aims of the study: (1) To identify the most significant and relevant factors for the occurrence of slides. This includes time-variable factors, to allow for the probability of slides occurrence varying with time. (2) To examine the correlation between each factor and slide occurrence, and to establish an assessment model of slide probability using these factors. (3) To verify or explain the application of the model established in the study for the prevention or mitigation of slides.

A number of international researchers have been investigating slide probability or hazard assessment. The majority of studies fall into three main categories: qualitative analysis, quantitative statistical analysis, and physical mechanism analysis (Aleotti and Chowdhury 1999; Guzzetti et al. 1999). In

general, qualitative analyses are based entirely on the results of human judgment and the implementation of an assessment of susceptibility to hazard. The input parameters for analysis usually are derived from field surveys supplemented by aerial photographs. Hence, they have been defined as expert evaluation approaches and can be divided into two types: field geomorphological analysis and the combination or overlaying of index maps with or without weighting (Leroi 1996; Soeters and Van Westen 1996; Barredo et al. 2000; Abella and Van Westen 2008).

Quantitative statistical analysis is based on actual cases of past slides, and screening for the factors that contribute to slide occurrence to determine their weighting. This is followed by bivariate or multivariate statistical methods to predict the probability of slide occurrence in regions where slides are yet to occur but which have similar combinations of factors (Michael-Leiba et al. 2003; Remondo, Bonachea, and Cendrero 2008; Jaiswal, Van Westen, and Jetten 2010).

Physical mechanism analysis utilizes engineering parameters to analyze specific sites or slopes in order to quantify their primary physical characteristics and to compute safety factors using specific mathematical models. These analytical models are usually employed in soil engineering to investigate slope stability, and they are widely used in civil engineering, engineering geology, slide assessment, and other areas (Duncan 1996; Griffiths and Lane 1999; Xie, Esaki, and Zhou 2004).

In summary, the factors which can be obtained conveniently and applied in large-area sites were considered in this study; accordingly, quantitative statistical analysis was employed to establish an assessment model for the probability of slide occurrence.

## 2. Materials and methods

### 2.1. Study site

The Kaoping River Basin was selected as the study site. The reason for this selection was the heavy impact of Typhoon Morakot on southern Taiwan in August of 2009, which caused numerous slides in the Kaoping River Basin, as well as severe loss of lives and property (there were 681 deaths and 18 missing persons). In addition, the slides led to an increased probability of future slides. The Kaoping River Basin is located in southern Taiwan. The highest peak is Yushan at 3952 m above sea level, the major river is 171.00 km in length, and its basin area spans 3256.85 km<sup>2</sup>. There are large differences in elevation in the terrain of the Kaoping River Basin, with about a maximum of 4000 m in the decline from the northeast to the southwest. The geographical location and stream system of the basin are shown in Figure 1.

### 2.2. Data collection and preprocessing

#### 2.2.1. Division of study site into slope-units

The study site was divided into slope-units that had minimal variations in their hydrological and physiographic characteristics, in order to analyze the probability of slide occurrence at different locations. This was achieved using the Hydrology module in the (ArcMAP) geographic information system software. To compute

the flow direction and catchment area of each grid, a 40-m digital elevation model (DEM) was used. Next, the Watershed tool analyzed, automatically, the ridgeline and water systems of slopes to identify the slope-units. This resulted in 231 slope-units, which were used in the construction of the assessment model for the probability of slide occurrence. They are shown in Figure 2.

#### 2.2.2. Rainfall data

The rainfall segmentation method proposed by Fan, Liu, and Wu (2003) was adopted to segment the rainfall data from each typhoon event. Relevant methods are summarized as follows:

##### (1) Selection of representative rainfall observation stations

Fan et al. (2013) had previously screened the Central Weather Bureau's rainfall observation stations using three factors: geographical location, rainstorm features, and past annual frequency of disasters. This gave six representative rainfall observation stations: Dajin, Xinfa, Yuyoushan, Majia, Jiasian, and Yuemei. This study adopted these six stations as the base points and computed the distance from each slope-unit to them. The rainfall stations within the catchment that were closest to the slope-units were selected as reference rainfall stations. The location of reference rainfall stations in the slope-units is shown in Figure 3.

##### (2) Rainfall segmentation

Fan, Liu, and Wu (2003) considered that due to the steep slopes and rapid rivers of the mountainous areas in Taiwan, runoff will flow extremely rapidly. Debris warnings should therefore include the contribution of previous rainfalls, as well as the fact that the early stages of the current rainfall will have a smaller impact on the triggering of debris flow.

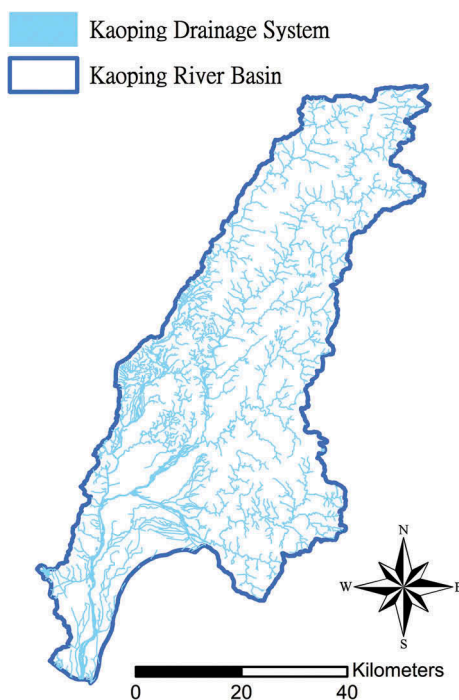


Figure 1. Stream system of the Kaoping River Basin.

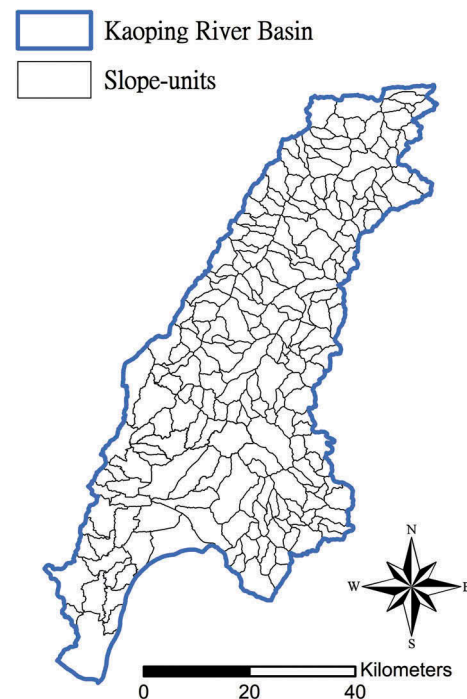


Figure 2. Division of slope-units.

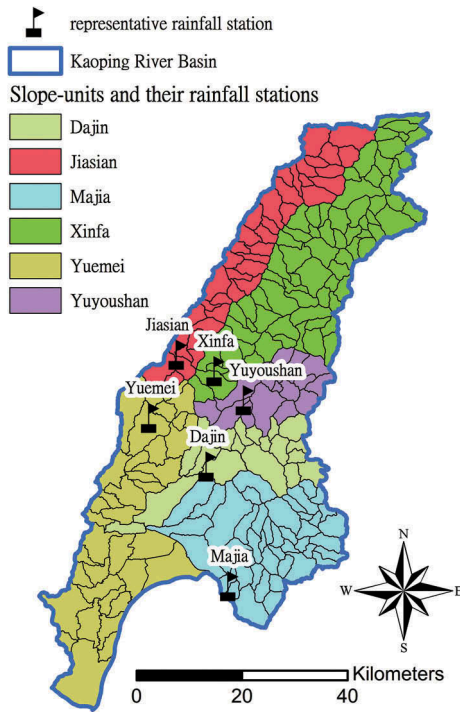


Figure 3. Distribution of reference rainfall stations.

Hence, they proposed that the time when cumulative rainfall reaches 10 mm in the most recent 24 h should be considered the start of rainfall, and the time when cumulative rainfall is less than 10 mm in the most recent 24 h as the end of rainfall. Fan, Liu, and Wu (2003) adopted this method to segment rainfall, which effectively enhanced the accuracy of warning models for debris flow. This study has adopted this method of segmenting rainfall events, and the results are shown in Figure 4.

2.2.3. Slides

ArcMap 10.1 was employed to overlay the landslide inventory map data from Formosat-2 images interpreted by the Central Geological Survey in Taiwan. Differences in landslide distribution before and after each typhoon event were identified as the result of slides caused by each typhoon, in order to

exclude the influence of factors other than typhoon events on the two landslide maps and to confirm those slides were triggered by typhoon events. The landslide maps before and after each typhoon event were filtered by no more than 200-mm precipitation at the relevant representative rainfall station and no earthquakes of more than 3 on the Richter scale having occurred at the study site. The maps included the landslide inventory before and after Typhoon Haitang in 2005 and Typhoons Talim (in 2005), Kaemi (in 2006), Morakot (in 2009), Nanmadol (in 2011), and so on. This yielded 826 cases with slides and 329 without slides.

2.3. Research methods

2.3.1. Identification of physiographic factors

The physiographic factors related to slide occurrence have been determined in many previous studies (e.g. Chang 1987; Keefer et al. 1987; Lee 2009; Pradhan and Lee 2010; others), mostly, through a subjective approach. Alternatively, a quantitative statistical method is adopted in this study. Seven common factors, which can be easily acquired, were first identified and verified in the subsequent tests. The selected factors are slope steepness  $S$ , mean elevation  $E_{avr}$ , elevation difference  $H$ , the road ratio  $RL$ , the dip slope ratio  $DS$ , the landslide ratio  $LR$ , and distance to fault  $DF$ . Table 1 describes their definitions and computation.

Further statistical tests were undertaken to analyze the correlation of each factor with slide occurrence, and the independence between factors. The Mann–Whitney U test and Spearman Rank Correlation tests are nonparametric tests that are suitable for non-normally distributed populations or small sample sizes. In general, the significance level of statistical tests is set at 0.1, 0.05, or 0.01, and test with  $p$ -values smaller than the significance levels indicates a significant correlation between the two samples. The significance level for the Mann–Whitney U test and Spearman Rank Correlation tests were set at 0.01 in this study.

2.3.2. Quantification of physiographic factors

Fan et al. (2015) previously utilized the genuine values of physiographic factors and their conversions to degrees of

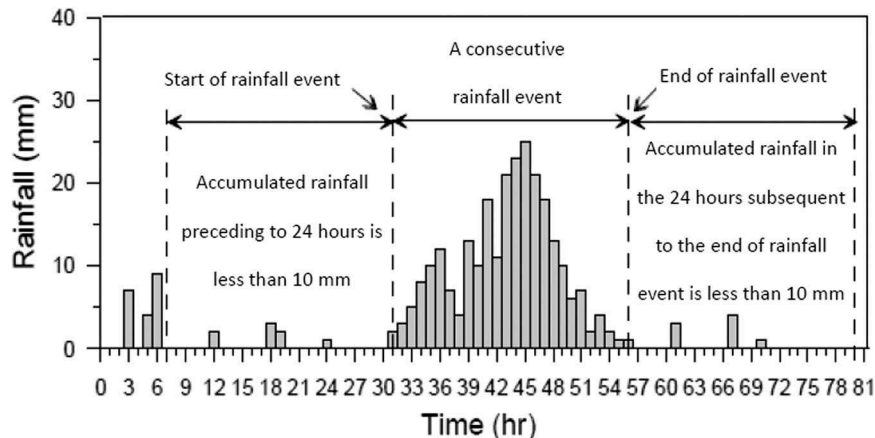


Figure 4. Segmentation of rainfall events proposed by Fan, Liu, and Wu (2003).

**Table 1.** Definition and computation of physiographic factors identified from previous studies.

No.	Item of factors	Definition	Computation
1	Elevation difference $H$	The difference between the highest and lowest elevations within a region.	Computed using the 1/25,000 DEM provided by the National Land Surveying and Mapping Center in Taiwan. Unit: meter.
2	Mean elevation $E_{av}$	The mean height relative to sea level within a region.	Computed using the 1/25,000 DEM provided by the National Land Surveying and Mapping Center in Taiwan. Unit: meter.
3	Slope steepness $S$	The arc tangent function of elevation difference and horizontal length.	$S = \tan^{-1}(\frac{H}{L})$ where $S$ denotes the slope steepness; $H$ denotes the elevation difference; $L$ denotes the horizontal length between the points at maximum and minimum elevation within a region. Unit: degree.
4	The road ratio $RL$	The length of roads per unit area.	Computed using the 2009 survey map data from the Directorate General of Highways in Taiwan, which includes provincial roads, county roads, urban roads, rural roads, and railway. $RL = \frac{L}{A}$ where $RL$ denotes the road ratio; $L$ denotes the length of roads within a region; $A$ denotes the total area of the region. Unit: 1/m
5	The dip slope ratio $DS$	The ratio between the area of the dip slopes and the total area within a region.	Computed using the dip slope map layer provided by the Central Geological Survey in Taiwan. $DS = \frac{A_1}{A}$ where $DS$ denotes the dip slope ratio; $A_1$ denotes the area of dip slopes within a region; $A$ denotes the total area of the region. Unit: Percent
6	The landslide ratio $LR$	The ratio between the area of landslides and the total area within a region; i.e. the recurrence of slides. The landslides include fall, topple, slide, lateral spread, and flow, as defined by Varnes (1978).	Computed using the landslide inventory map data from Formosat-2 images interpreted by the Central Geological Survey in Taiwan. $LR = \frac{A_2}{A}$ where $LR$ denotes the landslide ratio; $A_2$ denotes the area of landslides within a region; $A$ denotes the total area of the region. Unit: Percent
7	Distance to fault $DF$	Reciprocal of the distance from a region to active faults.	Computed using the active fault map layer provided by the Central Geological Survey in Taiwan. $\begin{cases} DF = 1/L \\ \text{if } L < 1\text{km, } DF = 1 \end{cases}$ where $DF$ denotes the distance to fault (1/km); $L$ denotes the distance from the center of a region to active faults (km).

membership in fuzzy sets (part of fuzzy theory) to compare their influence on an assessment model for the probability of the occurrence of debris flow. Their study verified that the conversion of physiographic factors by membership function could prevent the problem of excessive dispersion in the genuine values and simultaneously accurately reflect their influence on the occurrence of debris flow. Therefore, this study used physiographic factors converted by membership function to establish an assessment model for the probability of slide occurrence.

### 2.3.3. Assessment model for the probability of slide occurrence

Logistic regression, a multivariate statistical analysis, was undertaken to analyze slide occurrence. Logistic regression has been widely used for the estimation of the likelihood of slides and debris flows. For example, Chang, Chiang, and Hsu (2007) and Chang and Chiang (2009) employed logistic regression to predict the occurrence of slides in the Chen-You-Lan River basin and Shimen Reservoir, respectively. Results showed that the predictions achieved 78% and 84% accuracy, respectively. Fan et al. (2015) assessed the impact of slides and other physiographic factors on the probability of debris flow in the Chen-You-Lan River basin. Through verification using a random selection of historical events, the accuracy of the probability model of debris flow occurrence was approximately 70–80%.

Logistic regression model is a special log-linear model with a binary-dependent variable (Agresti 2002). It may be calculated by

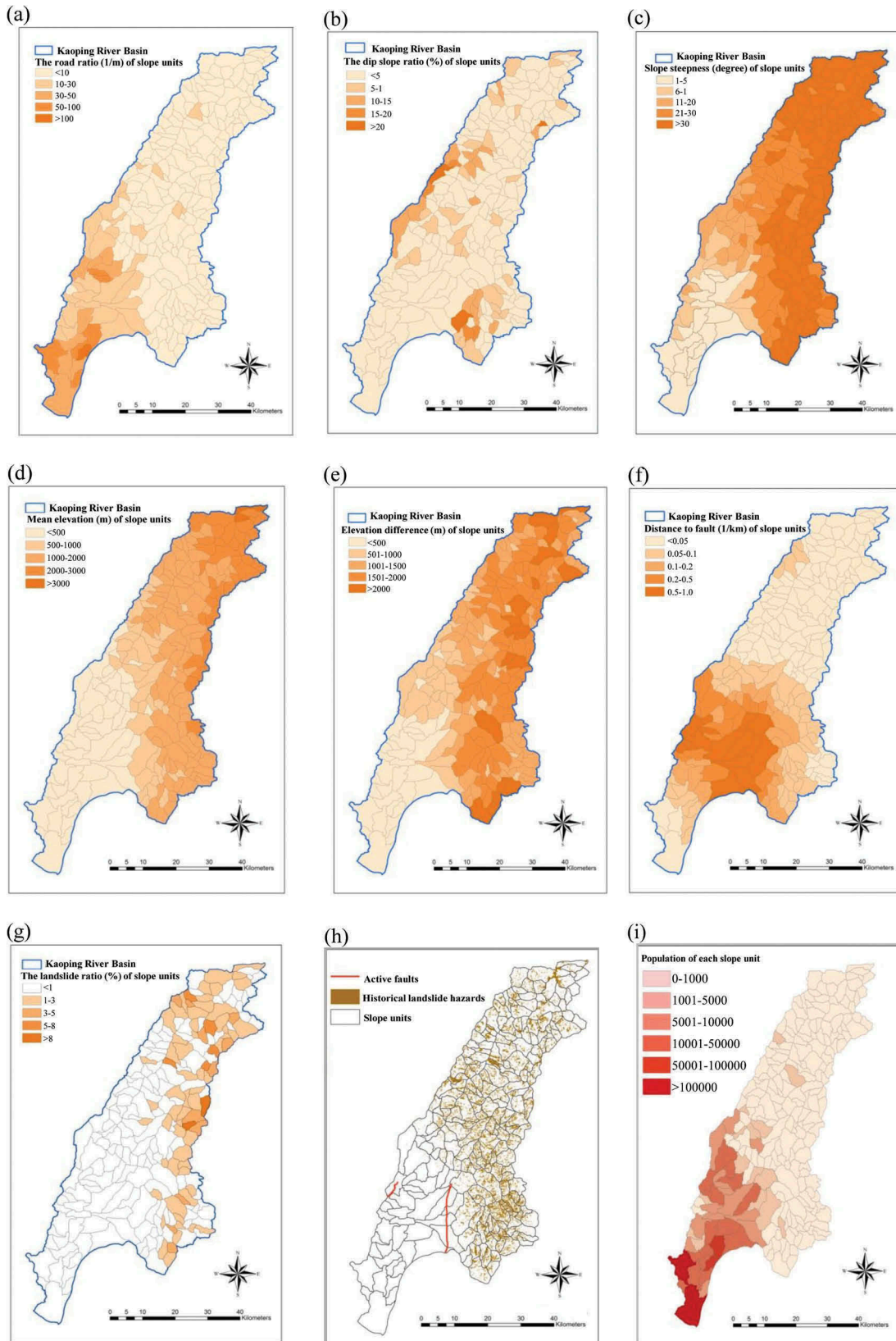
$$\begin{cases} Z_i = \ln\left(\frac{P_i}{1-P_i}\right) = \alpha + \sum_{k=1}^k \beta_k x_{ki} \\ P_i = \frac{\exp(Z_i)}{1+\exp(Z_i)} \end{cases}, \quad (1)$$

where  $P_i$  is the probability of event occurrence at point  $i$  given a series of independent variables  $x_{1i}, x_{2i}, \dots, x_{ki}$  and  $\alpha$  and  $\beta_k$  are coefficients.

In this study,  $x_{ki}$  is the factor vector at point  $i$  where, if there is a slide hazard, then  $P_i = 1$ ; if there is not, then  $P_i = 0$ . Regression analysis was performed on the training data to obtain  $\alpha$  and  $\beta_k$ . The variables used in the regression model consisted of known physiographic factors from earlier studies and the rainfall factors obtained by the rainfall segmentation method proposed by Fan, Liu, and Wu (2003).

The assessment model for the probability of slide occurrence was established through the two stages of training and validation. The values of the model coefficients were determined during the training phase. The values estimated by the model were tested against actual values, and the accuracy and reliability of the model's estimations were investigated. Nevertheless, during actual slide hazards there is a far higher proportion of samples with slides than samples without slides, resulting in the model's estimation of the likelihood of non-slide being more accurate. The study by Can et al. (2005) demonstrated that accuracy improved with logistic regression models of slides while the ratio of 'slide events (which had happened) to non-slide events (which had not happened)' is 1. This





**Figure 5.** Distribution of physiographic factors and slide hazards: (a) distribution of the road ratio; (b) distribution of the dip slope ratio; (c) distribution of slope steepness; (d) distribution of mean elevation; (e) distribution of elevation difference; (f) distribution of the factor of distance to fault; (g) distribution of the landslide ratio (using pre-Typhoon HaiTang as example); (h) distribution of historical slide cases and the factor of distance to fault; (i) population density of study site (March 2012 statistical data from the Household Registration Office).

**Table 4.** Results of Spearman Rank test for non-time-variable physiographic factors.

		The dip slope ratio	Slope steepness	Mean elevation	Elevation difference
Correlation coefficient	The dip slope ratio	1	0.102	0.08	0.237
	Slope steepness	0.102	1	0.805	0.769
	Mean elevation	0.08	0.805	1	0.744
	Elevation difference	0.237	0.769	0.744	1
Significance	The dip slope ratio	–	0.123	0.225	<0.01
	Slope steepness	0.123	–	<0.01	<0.01
	Mean elevation	0.225	<0.01	–	<0.01
	Elevation difference	<0.01	<0.01	<0.01	–

recorded slope-unit information. The explanation is set out below:

(1) Slope steepness  $S$

The degree of membership  $S_N$  for the slope steepness factor is given by

$$S_N = \begin{cases} 0.00023 \times S^{2.283} \\ 1, \text{ if } S \geq 39.23^\circ \end{cases} \quad (2)$$

where  $S$  means the slope steepness ( $^\circ$ ). Equation (2) is obtained in accordance with  $r^2 = 0.9447$ , where  $r$  is the correlation coefficient and  $r^2$  is its determination. As shown in Equation (2) and Figure 6(a), the upper limit of the slope is defined as  $39.23^\circ$ , which implies that when the  $S$  is greater than  $39.23^\circ$ , further increases in  $S$  will not affect its influence on slide occurrence.

(2) The dip slope ratio  $DS$

The degree of membership  $DS_N$  for the dip slope ratio factor is given by

$$DS_N = 1 - \exp(-21.01 \times DS), \quad (3)$$

where  $DS$  means the dip slope ratio. The membership function and degree of membership for the dip slope ratio are shown in Equation (3) and Figure 6(b), where Equation (3) is obtained in accordance with  $r^2 = 0.9922$ .

(3) The landslide ratio  $LR$

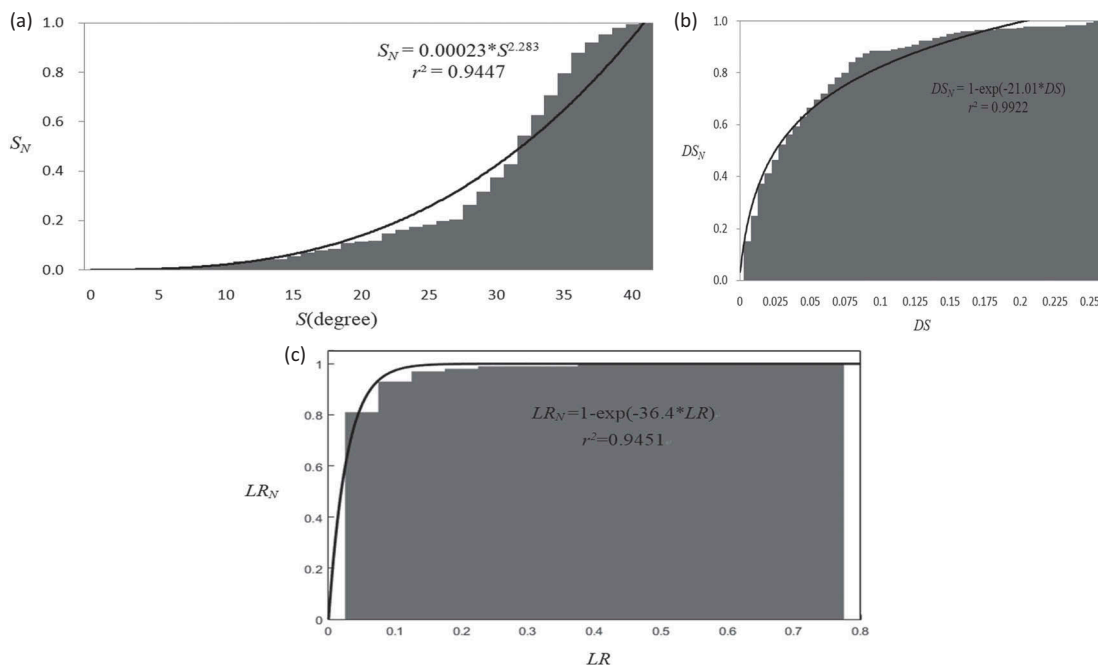
The degree of membership  $LR_N$  for the landslide ratio factor is given by

$$LR_N = 1 - \exp(-36.4 \times LR), \quad (4)$$

where  $LR$  means the landslide ratio. The membership function and degree of membership for the landslide ratio are shown in Equation (4) and Figure 6(c), where Equation (4) is obtained in accordance with  $r^2 = 0.9451$ .

**3.2. Construction of assessment model for the probability of slide occurrence**

All of the slope-units were assigned to six representative rainfall stations (see Figure 3), so that the records of cumulative rainfall



**Figure 6.** Degree of membership of physiographic factors including the following: (a) slope steepness ( $S$ ); (b) the dip slope ratio ( $DS$ ); (c) the landslide ratio ( $LR$ ).

in each typhoon event can be taken as the hydrological factor of the slope-unit. This was combined with the slope steepness, the dip slope ratio, and the landslide ratio that had been selected after correlation and independence testing, to construct the assessment model of slide occurrence. The classification error matrix was used to evaluate sensitivity, specificity, and overall accuracy in order to determine the model's performance. Two thousand iterations of random sampling were performed during the model's construction, and the mean model sensitivity, specificity, and overall accuracy were all stabilized. In order to ensure that all the factors included in the model were standardized, the cumulative rainfall also underwent membership function conversion. The degree of membership  $R_N$  for the cumulative rainfall factor is given by

$$R_N = 0.0006 \times R - (8.9 \times 10^{-8})R^2, \quad (5)$$

where  $R$  is the cumulative rainfall (mm). Equation (5) is obtained in accordance with  $r^2 = 0.9559$ .

The model regress result  $Z$  is then determined by

$$\begin{aligned} Z &= \ln\left(\frac{P}{1-P}\right) \\ &= 4.875 \times S_N + 0.468 \times DS_N + 2.521 \times LR_N + 2.761 \times R_N \\ &\quad - 4.088, \end{aligned} \quad (6)$$

where  $S_N$  is the degree of membership of slope steepness,  $DS_N$  is the degree of membership for the dip slope ratio,  $LR_N$  is the degree of membership of the landslide ratio and  $R_N$  is the degree of membership of cumulative rainfall, and  $P$  is the probability of slide occurrence. Model accuracy is shown in Table 5.

As Table 5 demonstrates, the sensitivity and specificity of the assessment model for the probability of slide occurrence, based on physiographic factors and hydrological factors, was approximately 80%. This indicates that the model established using the research method described in this paper has rather satisfactory slide prediction capability.

As for the physical mechanisms of slide occurrence, the  $Z$  value increased as the slope steepness, the dip slope ratio, and the landslide ratio of the slope-unit increased; thus, a high  $Z$  value indicates a higher probability of slide occurrence. In terms of Equation (6), the lowest  $Z$  value was  $-4.088$ , and the corresponding probability of slide occurrence was very small, about 0.0165. Since this value is relatively insignificant in practical terms, the minimum probability of slide occurrence can be regarded as zero (0). Similarly, as  $Z$  continued to increase, the actual probability of slide occurrence also increased, eventually approaching 1. Therefore, the range of probabilities for slide occurrence was consistent with actual physical mechanisms and can be considered reasonable.

**Table 5.** Accuracy of assessment model for probability of slide occurrence.

Training stage			Validation stage		
Sensitivity	Specificity	Overall accuracy	Sensitivity	Specificity	Overall accuracy
79.9%	81.9%	81.2%	79.5%	81.8%	81.3%

### 3.3. Influence of the landslide ratio on the probability of slide occurrence

In terms of time series and actual circumstances, slope steepness and the dip slope ratio do not change significantly with time, whereas cumulative rainfall and the landslide ratio might change with time and accordingly are the main variables causing the change of slide occurrence. Therefore, at a given value of slope steepness and the dip slope ratio, one can compute the relationship between the landslide ratio and cumulative rainfall with the probability of slide occurrence. As can be seen in Equation (6), cumulative rainfall and the landslide ratio were positively correlated with the probability of slide occurrence. Nevertheless, at a specific known value of the probability of slide occurrence, cumulative rainfall and the landslide ratio are negatively correlated with each other. In addition, using slope-unit 64 and 118 as examples, the genuine values and degrees of membership of the physiographic factors in these areas are shown in Table 6. The contour maps showing the relationship among the probability of slide occurrence, the landslide ratio, and cumulative rainfall with slide occurrence are shown in Figures 7 and 8.

Overall, although the slope-units had different physiographic parameters due to geomorphological differences, the parameters had similar trends of influence on the probability of slide occurrence. In fact, the positive correlations of cumulative rainfall ( $R$ ) and the landslide ratio ( $LR$ ) with the probability of slide occurrence ( $P$ ) were consistent with physical implications. As can be seen from Figures 7 and 8, as cumulative rainfall ( $R$ ) and the landslide ratio ( $LR$ ) increased gradually, the probability of slide occurrence ( $P$ ) increased dramatically; when cumulative rainfall ( $R$ ) and the landslide ratio ( $LR$ ) exceeded a certain value, the probability of slide occurrence ( $P$ ) continued to increase, but began to plateau until the probability ( $P$ ) approached 1.

If a region has a high landslide ratio, then lower rainfall is able to induce the recurrence of slides. In order to lower the probability of slide occurrence, reducing the landslide ratio would be an effective measure. Therefore, the reduction of slope exposure and loose soil through landslide management should be a key strategy in the prevention of slide recurrence. Using slope-unit no.64 as an example, with a landslide ratio of 10% and the Kaoping River Basin 25-year return period of 24 h cumulative rainfall of about 600 mm, the probability of slide occurrence ( $P$ ) was estimated using Equation (6) as 0.79 (i.e. 79%). Under the same cumulative rainfall, if the landslide ratio of that region is reduced to 1% through engineering measures or vegetation restoration, then the probability of slide occurrence ( $P$ ) will drop to 0.41 (i.e. 41%), thus significantly reducing the risk of slides in this region. Therefore, the model developed in this study can assist in prediction of slide occurrence and the proposed subsequent engineering measures or vegetation restoration is able to reduce the landslide ratio and the probability of slide occurrence.

**Table 6.** Physiographic conditions of selected slope-units.

Slope-unit no.	Slope steepness		The dip slope ratio	
	Genuine value (degree)	Degree of membership	Genuine value (%)	Degree of membership
64	26.72	0.42	0.002	0.042
118	22.42	0.28	0.059	0.71

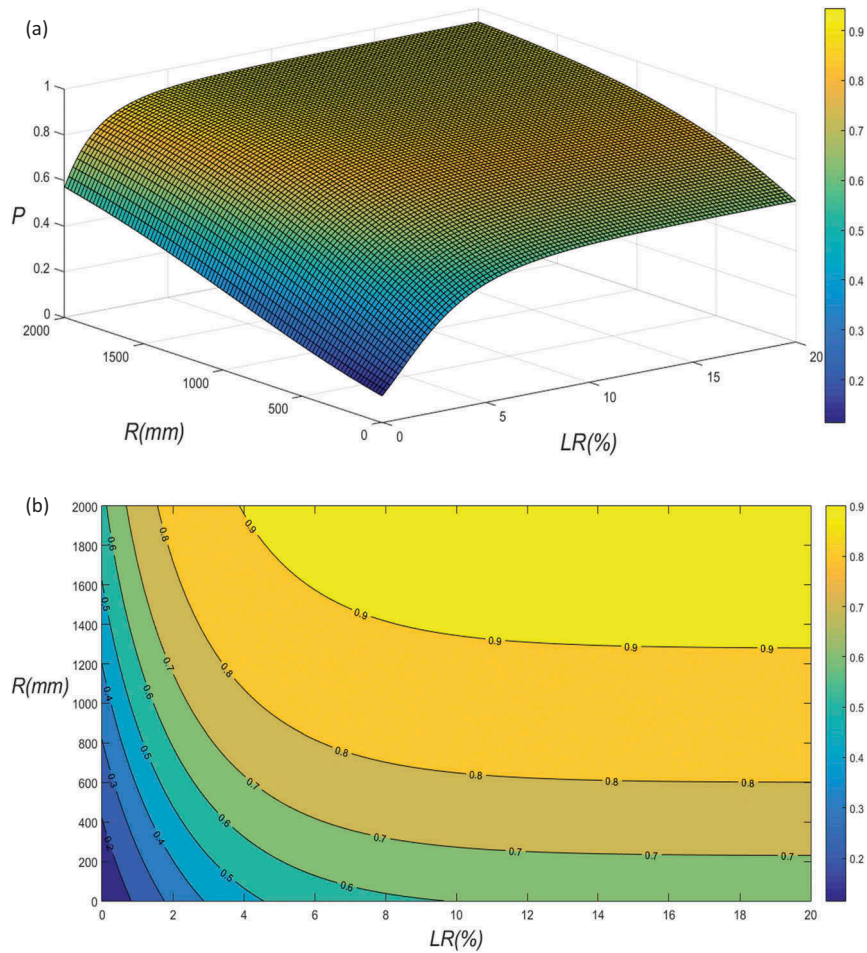


Figure 7. (a) The relationship of probability of slide occurrence ( $P$ ), cumulative rainfall ( $R$ ), and the landslide ratio ( $LR$ ) in slope-unit no.64; (b) contour map of slide occurrence in slope-unit no.64.

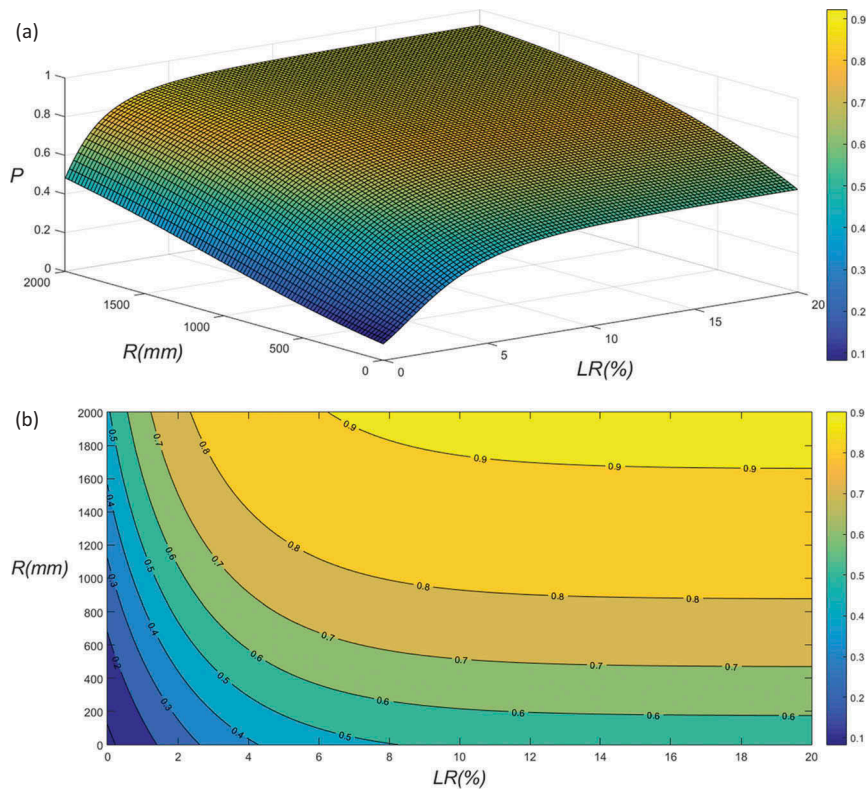


Figure 8. (a) The relationship of probability of slide occurrence ( $P$ ), cumulative rainfall ( $R$ ), and the landslide ratio ( $LR$ ) in slope-unit no.118; (b) contour map of slide occurrence in slope-unit no.118.

**Table 7.** Comparison of model-estimated probabilities and actual conditions.

Typhoon events	Slope-unit No.	Cumulative rainfall (mm)	Slope steepness (°)	The dip slope ratio (%)	The landslide ratio (%)	Probability estimated via logistic regression	Actual slide occurrence
Kaemei (23 July 2006–26 July 2006)	202	577.5	38.3495	11.43	7.87	0.9855	No
HaiTang (16 July 2005–20 July 2005)	39	1562	35.2201	3.49	0.76	0.9286	Yes
Namadol (27 August 2011–31 August 2011)	4	301	36.4943	4.05	3.17	0.9252	Yes
Morakot (5 August 2009–10 August 2009)	143	1508	28.8436	9.95	2.60	0.9021	Yes
Namadol (27 August 2011–31 August 2011)	108	594.5	31.0260	0.63	7.83	0.8906	Yes
Talim (30 August 2005–1 September 2005)	73	608.5	35.9226	1.57	0.80	0.8297	Yes
Kaemei (23 July 2006–26 July 2006)	203	577.5	30.7157	17.09	1.31	0.7279	Yes
Talim (30 August 2005–1 September 2005)	24	586	33.6943	6.50	0.14	0.6712	Yes
Talim (30 August 2005–1 September 2005)	68	586	33.1784	11.97	0.00	0.6350	No
Talim (30 August 2005–1 September 2005)	99	608.5	31.7210	0.00	0.24	0.5113	Yes
HaiTang (16 July 2005–20 July 2005)	97	1298.5	21.9243	0.33	0.04	0.2702	Yes
Namadol (27 August 2011–31 August 2011)	121	409	17.3627	4.53	1.10	0.1713	No
Namadol (27 August 2011–31 August 2011)	119	281	15.0357	1.86	1.99	0.1618	Yes
HaiTang (16 July 2005–20 July 2005)	98	1298.5	14.1340	0.09	0.00	0.1338	No
Namadol (27 August 2011–31 August 2011)	98	301	14.1340	0.09	1.83	0.1298	No
Morakot (5 August 2009–10 August 2009)	169	1508	1.3500	0.00	0.08	0.1120	No
HaiTang (16 July 2005–20 July 2005)	126	1149	10.7961	0.13	0.00	0.0962	No
Kaemei (23 July 2006–26 July 2006)	172	159.5	10.2976	1.45	0.00	0.0300	No
Talim (30 August 2005–1 September 2005)	225	376.5	0.6802	0.00	0.00	0.0294	No
Namadol (27 August 2011–31 August 2011)	227	281	1.3605	0.00	0.00	0.0256	No

In the future, the regional probability of slide occurrence can be updated rapidly to reflect changes in physiographic factors. Given an appropriate cumulative rainfall and an acceptable risk of slide occurrence, the model can identify priority regions for slide prevention in the watershed.

Further random sampling of 10 actual slides and 10 sites without slides for probability estimation using Equation (6) for comparison are shown in Table 7. Although the model could not predict actual cases with 100% accuracy, giving two false alarms and two false negatives, the overall accuracy was maintained at 80%. Thus, the model's estimation of the probability of slide occurrence in a region above 0.5 was relatively reliable. As for the 20% that cannot be managed by the model, the primary reason appears to be uncertainty as to whether the factors obtained truly reflect the actual circumstances. Using cumulative rainfall as an example, the observed cumulative rainfall for the slope-units during slide occurrence was obtained from their respective representative rainfall stations. Hence, the actual cumulative rainfall in that region may deviate from the observed

values due to temporal or spatial factors, thus causing uncertainties beyond the reach of the model.

#### 4. Conclusions

By carrying out a literature review, followed by correlation and independence tests, slope steepness, the dip slope ratio, and the landslide ratio (a time-variable factor) were identified as factors significantly correlated to slide occurrence. The physiographic and hydrological (cumulative rainfall) factors were then applied to establish an assessment model composed of slide-triggering mechanisms for the probability of slide occurrence. Among them, the management of the landslide ratio is a key factor in reducing the risk of slides. Engineering measures and vegetation restoration can be utilized as tools to reduce the landslide ratio as indicated in Section 3.3. It is seen that the probability of slide occurrence is significantly reduced. Therefore, the model established in this study can assist in prediction of slide occurrence, and the proposed

subsequent engineering measures or vegetation restoration is able to reduce the landslide ratio and the probability of slide occurrence.

After the landform has been apparently changed due to earthquakes, typhoons, or human development, using this model, the rainfall threshold for slide occurrence can be adjusted by updating the physiographic factors. Further, given an appropriate cumulative rainfall and an acceptable risk of slide occurrence, the model can identify priority regions for slide prevention in the watershed. Besides, 10 actual slides and 10 sites without slides were randomly selected as samples from the historical rainfall events to verify the assessment model established in this study. The results showed that the model accuracy was approximately 80%, if the probability threshold  $P_{sh}$  is set to be 0.5. This was consistent with overall accuracy in the training and validation stages, with two false alarms and two false negatives.

## Nomenclature

$DF$	Distance to fault
$DS$	The dip slope ratio
$DS_N$	The degree of membership for $DS$
$E_{av}$	Mean elevation
$H$	Elevation difference
$LR$	The landslide ratio
$LR_N$	The degree of membership for $LR$
$P_i$	The probability of slide occurrence at point $i$
$P_{sh}$	Probability threshold of slides occurrence
$r$	Correlation coefficient
$r^2$	Determination of correlation coefficient
$R$	The cumulative rainfall
$R_N$	The degree of membership for $R$
$S$	Slope steepness
$S_N$	The degree of membership for $S$
$X_{ki}$	The factor vector at point $i$
$Z$	The function of logistic regression model
$\alpha$ and $\beta_k$	Coefficients in the function of logistic regression model

## Disclosure statement

No potential conflict of interest was reported by the authors.

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