Multifactor analysis and simulation of the surface runoff and soil infiltration at different slope gradients

J Huang¹,²,³, Q Kang¹,², J X Yang¹,² and P W Jin¹,²

¹Soil and Water Conservation Monitoring Center of Pearl River Basin, Guangzhou 510611, China
²Pearl River Hydraulic Research Institute, Guangzhou 510611, China
E-mail: hjnwsuaf@outlook.com

Abstract. The surface runoff and soil infiltration exert significant influence on soil erosion. The effects of slope gradient/length (SG/SL), individual rainfall amount/intensity (IRA/IRI), vegetation cover (VC) and antecedent soil moisture (ASM) on the runoff depth (RD) and soil infiltration (INF) were evaluated in a series of natural rainfall experiments in the South of China. RD is found to correlate positively with IRA, IRI, and ASM factors and negatively with SG and VC. RD decreased followed by its increase with SG and ASM, it increased with a further decrease with SL, exhibited a linear growth with IRA and IRI, and exponential drop with VC. Meanwhile, INF exhibits a positive correlation with SL, IRA and IRI and VC, and a negative one with SG and ASM. INF was going up and then down with SG, linearly rising with SL, IRA and IRI, increasing by a logit function with VC, and linearly falling with ASM. The VC level above 60% can effectively lower the surface runoff and significantly enhance soil infiltration. Two RD and INF prediction models, accounting for the above six factors, were constructed using the multiple nonlinear regression method. The verification of those models disclosed a high Nash-Sutcliffe coefficient and low root-mean-square error, demonstrating good predictability of both models.

1. Introduction
The surface rainfall and soil infiltration are the key factors affecting the soil erosion [1,2] by a highly nonlinear dynamic mechanism influenced by many factors. Studies on the runoff yield and soil permeability for individual rainfall events are very important for understanding and controlling erosion processes [3].

The rainfall is the dominant factor controlling the surface runoff and soil infiltration. The higher the rainfall amount, the higher the runoff volume [4]. A greater rainfall intensity does not necessarily lead to higher soil infiltration [5]. When the rainfall intensity is relatively small, its increase can induce the
better permeability, but an excessive rain intensity may damage the top soil structure and seal the soil, as well as significantly reduce the infiltration rate [6, 7]. The slope gradient and length significantly influence the runoff and infiltration. Fox et al [8] proved indirectly that the runoff volume was growing with the slope gradient under laboratory conditions. However, Govers [9] has revealed the opposite trend under field conditions. With other influence factors kept constant, the runoff volume became larger with the slope length, when the latter was relatively small [10]. However, when the slope length exceeds a threshold value, the runoff volume displays a downward trend [11, 12]. Janeau et al [13] found that the steady final infiltration rate increased sharply as a result of a growing slope gradient in a series of laboratory experiments with 1.0 m² soil bins. Although there is no consensus on the slope gradient/length effects on the runoff and infiltration, the existence of the slope gradient and length threshold values is widely supported in studies [14-16]. The vegetation cover influences the runoff and infiltration changing the rainfall-runoff-infiltration process on the slopes [17, 18]. The vegetation cover can significantly reduce the surface runoff by the interception of the rainfall, and increase the soil infiltration by reducing raindrop impacts [1]. The antecedent soil moisture is also considered the important factor controlling the runoff and infiltration [19-21]. The more the antecedent soil moisture and less the infiltration capacity, the larger the runoff volume [22]. However, Luk [23] indicated that effect of the antecedent moisture was not only confined to the enhanced runoff capacity in the tested soils, having the cohesive structure.

Since most previous studies discussed the effect of only one or two factors on the slope runoff or soil infiltration, it is topical to elucidate the effect of multiple factors on their patterns. Therefore, the object of this study, making use of the field data, is to (1) investigate the quantitative relationships between the slope runoff, soil infiltration and the influence factors, and (2) construct the prediction model of the slope runoff and soil infiltration in the course of individual rainfall events.

2. Materials and methods

2.1. Site description

![Figure 1. Localities of the five experimental catchments.](image-url)
The data were obtained in the course of natural rainfall events from 261 runoff plots of five field catchments in the southern China. The localities of these five catchments are depicted in figure 1. Main soil types and vegetation species, as well as several physical soil properties of the soil for these five catchments are shown in table 1. These five catchments (sites A, B, C, D and E) have 10, 12, 12, 13 and 8 runoff plots of different sizes, whose detailed parameters are also given in table 1.

### Table 1. Several physical properties of the experimental catchments and runoff plot sizes.

| Sites | Main soil types | Main vegetation species                      | Composition | Runoff plots |
|-------|-----------------|----------------------------------------------|-------------|--------------|
|       |                 |                                              | Clay, %     | Gradient, °  | Length, m  | Width, m  |
| A     | Red soil Purple soil | Orange tree Masson pine                     | 31.8        | 5            | 20, 60     | 5          |
|       |                  |                                              | 42.1        | 15           | 10, 20, 100|            |
|       |                  |                                              | 26.2        | 20           | 10, 20     |            |
|       |                  |                                              | 23.1        | 25           | 20, 100    |            |
| B     | Red soil        | Pinus yunnanensis Pear tree                 | 27.4        | 5            | 20, 60     |            |
|       |                  |                                              | 35.3        | 15           | 10, 100    |            |
|       |                  |                                              | 37.3        | 20           | 10, 20, 100|            |
|       |                  |                                              | 26.9        | 25           | 20, 100    |            |
| C     | Yellow soil     | Juniperus indica Cryptomeria               | 53.1        | 5            | 20, 60     |            |
|       |                  |                                              | 15.7        | 15           | 10, 20     |            |
|       |                  |                                              | 31.3        | 20           | 10, 20, 100|            |
|       |                  |                                              | 42.9        | 25           | 20, 100    |            |
|       |                  |                                              |             | 30           | 20         |            |
| D     | Red soil Yellow soil | Peach tree White popinac                  | 40.7        | 5            | 20, 60     |            |
|       |                  |                                              | 44.9        | 15           | 10, 20, 100|            |
|       |                  |                                              | 14.3        | 20           | 10, 20, 100|            |
|       |                  |                                              | 22.2        | 25           | 20, 100    |            |
| E     | Red soil        | Eucalyptus Masson pine                      | 42.6        | 5            | 60          |            |
|       |                  |                                              | 9.1        | 15           | 10, 20, 100|            |
|       |                  |                                              | 48.3        | 20           | 20, 100    |            |
|       |                  |                                              | 9.5         | 25           | 20, 100    |            |
2.2. Measurements

The runoff volume for a given period was used to randomly determine the frequency of measurements (ranging from 5 min to 30 min) for the collection of the surface runoff volume with a cylindrical container of a 3000 mL volume. After the collection and clarification of turbid water, the clear water volume was regarded as the runoff volume. The deposited sediment was air-dried and weighted to determine the sediment yield. The rainfall data were measured automatically by an electronic rain gauge.

There was one sample point per 25 m² to collect soil samples for determining soil moisture, and moisture levels were measured by the oven drying method. For each plot, the soil sampling points should be uniformly distributed over the slope surface. According to the weather forecast information, soil moisture measurements were carried out before the rainfall and, as soon as possible, after it.

The crown cover and undergrowth were assessed by the photographic method [1]. The specific steps are as follows: firstly, take three to five JPEG format photos with a digital camera to record the data on the current state of the crown cover and undergrowth; secondly, convert the JPEG photos into the ITFF format with a lab color channel using the Photoshop software package; finally, the crown cover and undergrowth are calculated using the Image-J software package. We chose three to five sampling points and repeated measurements 2-3 times per sampling point in each plot. The average value of the crown cover and undergrowth was regarded as the vegetation cover.

For a given individual rainfall event, let IRA, RD, INT represent the rainfall amount, runoff volume and vegetation intercept water, respectively, and assume that the evaporation and water filling of the concave over the slope surface during rainfall are negligible. Based on the water balance equation, the soil infiltration water (INF) can be assessed from the following expression:

\[
INF = IRA - RD - INT
\]  

(1)

Here the INT calculation refers to our previous study, and detailed information can be found elsewhere [24].

3. Results

3.1. Correlation between runoff depth, soil infiltration and influence factors

Results of the Pearson analysis of correlation between the runoff depth (RD) and soil infiltration (INF) for individual rainfall events and six influence factors are shown in figure 2. All the correlation coefficients reached the significance level (P≤0.01) except for the one between RD and the slope length (SL). The coefficient between RD and the individual rainfall amount (IRA) was positive and the highest. The relationships between RD and the individual rainfall intensity (IRI) and the antecedent soil moisture (ASM) were also positive, and their coefficients were 0.621 and 0.673, respectively. The slope gradient (SG) and vegetation cover (VC) exhibited a strong negative correlation with RD, with their coefficients equal to 0.503 and 0.705, respectively. The coefficient for IRA, IRI and INF was positive and maximum, while that for ASM and INF was negative and minimum. The results indicate that INF increased with IRA and IRI, but decreased with an increase in ASM. The relationships between SL, VC and INF were positive and their correlation coefficients were equal to 0.573 and 0.589, respectively (P≤0.01). The correlation coefficient for SG and INF was the least and equaled 0.442.
**Figure 2.** Pearson analysis of correlation between the runoff, infiltration and influence factors (N=363). (***) significant at P≤0.01. (ns) insignificant.

### 3.2. Analysis and simulation of runoff depth

The scatter diagrams for the average values of RD, INF and six factors were plotted, in order to study the quantitative relationship between RD and INF and influence factors for individual rainfall events as shown in figures 3 and 4.

RD came down followed by its growth with SG increase from 5° to 35°. The fitted equation reached the significance level, and the coefficient of determination R² was 0.944. Assuming that the first derivative of the fitted equation is equal to zero, the hump (knee point) on the fitted curve was obtained as (20.35°, 1.20 mm). RD was growing followed by a fall with SL increase from 10 to 100 m. However, the fitted equation did not reach the significance level, and the knee point was located at (54.22 m, 17.70 mm). RD increased consistently as a result of an increase in IRA and IRI. Both fitted equations reached the significance level with R² being equal to 0.902 and 0.857, respectively. The fitted equation for RD and the vegetation cover (VC) displayed an exponential pattern, acquiring the significance level. RD went down sharply with VC for VC<50%, while a drop of RD was slight for VC>50%. RD decreased with a following rise with ASM. The fitted equation reached the significance level and R² was 0.9553. The negative hump (knee point) was observed at (10.01%, 1.25 mm), so RD fell down consistently with ASM for ASM<10.01%, while RD grew persistently for ASM>10.01%.

Based on the fitted relationships between RD and influence factors as shown in figure 3, the following multi-parameter nonlinear model for predicting RD was constructed by the regression analysis considering 70% of the data:

\[
RD = \frac{SG^2 - 23SG - 0.2SL^2 + 18SL + 6IRA + 7IRI}{100} + 4.6e^{\frac{3VC}{100}} + \frac{ASM^2 - 22ASM - 39}{100}
\]  

(2)

R² in equation (2) is equal to 0.9095 (P<0.001), and the residual sum of squares (RSS) is 1.709. All of the regression coefficients in equation (2) reached the significance level (P<0.001) by the T-test.
Figure 3. Runoff depth as a function of: (a) slope gradient, (b) slope length, (c) individual rainfall amount, (d) individual rainfall intensity, (e) Vegetation cover, and (f) antecedent soil moisture. Note: Blue curves represent the confidence intervals at different significance levels.

3.3. Analysis and simulation of soil infiltration

INF displayed an increase followed by its fall with SG, but the fitted equation possessed poor correlation. The knee point on the fitted curve was (18.16°, 67.06 mm). In general, INF raised as a result of SL enlargement, but the fitted equation did not reach the significance level, and $R^2$ was relatively low. INF was growing with IRA and IRI. The two fitted equations reached the significance level, and $R^2$ values were 0.9919 and 0.9383, respectively. It is noteworthy that an increment of INF rate was relatively small for $IRI<20\ \text{mm h}^{-1}$ but became higher for $IRI>20\ \text{mm h}^{-1}$. INF increased logistically with VC. The fitted equation reached the significance level, and $R^2$ was 0.9154. Obviously, the INF variation with VC can be negligible when $VC<60\%$, but it grew dramatically for $VC>60\%$. INF was going linearly with ASM, and the fitted equation reached the significance level.

The multi-parameter nonlinear model for predicting INF was constructed by the regression analysis considering 70% of the data, based on the fitted relationships between INF and influence factors as shown in figure 4. The following equation was derived:

$$\begin{align*}
\text{INF} &= \frac{SG^2 - 29SG + 2SL + 86IRA - 8IRI}{100} - \frac{368.6}{1 - 495.3VC^{10.2}} - \frac{3ASM}{100} + 3.6
\end{align*}$$

(3)

$R^2$ and RSS are equal to 0.9941 ($P<0.05$) and 2.1569, respectively. All the regression coefficients in equation (3) reached a significance level ($P<0.05$) by the T-test.
4. Discussion

The relationship between the six influence factors and the runoff and infiltration for individual rainfall events is systematically analyzed to get a deeper insight into the slope runoff and soil infiltration behavior. The correlation coefficients for IRA, IRI and RD, INF were over 0.60 (P≤0.01), indicating that the rainfall is a very important factor controlling RD and INF values. This was confirmed by earlier studies of Garcia-Rodeja and Gil-Sotres [25] and Huang et al [26, 27]. Although higher infiltration rates are often observed with greater IRI, there appears to be no consensus in the literature on the explanation of this phenomenon [28]. Huang et al [5] found that the soil infiltration rate grew with IRI until a critical threshold was reached, its value ranging from 90 to 150 mm h⁻¹. VC can change the rainfall-runoff-infiltration mechanism and then affect the soil infiltration and slope runoff [29, 30]. The results of this study demonstrate that their coefficients were 0.705 and 0.589 (P≤0.01), respectively. RD fell exponentially and INF grew logistically with VC. INF increased sharply and a reduction in RD was almost invariant when VC>60%. Previous studies by Marston [31] and Zhu et al [32] also proved that VC of 40-60% or more can significantly reduce runoff and increase infiltration. Karnieli and Ben-Asher [21], Ceballos and Schnabel [19] and Fitzjohn et al [20] suggested that ASM can also be an important factor controlling the slope runoff and soil infiltration. Zehe et al [33] indicated that ASM at the forest site can explain 92% of the variability in the runoff coefficients. The higher the ASM, the lower the soil permeability and INF, and the larger the RD. In general, RD became higher and INF lower as a result of increase in ASM. The coefficients of SG correlation with RD and INF were 0.503 and 0.442, respectively (P≤0.01), indicating that SG is an important factor controlling the slope runoff and soil infiltration [8, 9]. In the present study, minimum RD and maximum INF values were observed for an SG value of about

![Figure 4](image-url)
20°. As is known from the literature, SL should have a significant impact on the runoff and infiltration [12, 34], but the correlation coefficient for SL and RD was only 0.276 and, thus, was insignificant. RD increased with its further decrease with SL, and SL=54.22 m was the inflection point of the curve. Ahead of this point, RD was continuously growing, while RD was going down consistently after this point.

The remaining 30% of the data were used to verify prediction models (2) and (3). The results depicted in figure 5 demonstrate a close of fit of the experimental and predicted results for both RD and INF. The Nash-Sutcliffe coefficient, root-mean-square error and correlation coefficient between experimental and predicted data were 0.9621, 1.1294, 0.9879 for RD and 0.9837, 1.9533, 0.9927 for INF, respectively, which indicates that equations (3) and (4) are applicable for predicting RD and INF values.

![Figure 5](image)

**Figure 5.** Observed and predicted values of the runoff depth (a) and infiltration (b) considering 30% of the data.

5. Conclusions

This study, based on the data from a series of natural rainfall events in the South of China, generated certain important information for better understanding of the quantitative relationships between the six factors (SG, SL, IRA, IRI, VC, ASM), runoff depth (RD) and infiltration (INF). An empirical model for RD and INF calculation based on the observation data using the above six factors is proposed. The results obtained are as follows:

The correlation coefficients for IRA, IRI, VC and RD were over 0.7 (P≤0.01), while those for IRA, IRI, ASM and INF approached 0.7 (P≤0.01). RD decreased followed by its increase with SG and ASM, it grew with a further fall with SL, linearly growing with IRA and IRI and falling exponentially with VC. Meanwhile, RD was rising consistently with SG for SG≤20.35°, and then falling continuously with SG for SG>20.35°. RD increased persistently with SL for SL<54.22 m and decreased consistently for SL>54.22 m. INF became higher and then lower with SG, linearly growing consistently with SL, IRA, and IRI, increased logistically with VC, and linearly lowering continuously with ASM. INF increased continuously with an increase in SG for SG<18.16° and was falling consistently for SG>18.16°. When VC was larger than 60%, RD was small and its reduction with an increase in VC was very slight, while INF was sharply growing. Two multi-parameter nonlinear models for predicting RD and INF were constructed using the regression analysis, and their applicability and feasibility were proved by the validation tests.
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