Optimization of revised universal soil loss equation of ecological forest lands in the hilly areas of the eastern Zhejiang Province

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Abstract. The soil erosion prediction model is an effective means to predict soil erosion and soil and water conservation planning. Based on the analysis of soil erosion law of typical economic forest slopes in the study area, it is of great significance to establish a prediction model for soil loss in typical economic forests in the study area. In this study, five typical economic forest slope runoff plots in the study area were used as research objects. The runoff and sediment data under natural rainfall conditions were used to optimize the universal soil loss equation. The prediction equation for soil and water loss in the hilly areas of the eastern Zhejiang Province was proposed: A= 0.004· R1.594· K· LS· C· P. The Nash efficiency coefficients of the simulation results are above 0.70, and the coefficients of determination are above 0.80.

1. Introduction

Slopes are widely found in nature, and over 80% of the entire land surface belongs to the slope. Therefore, the occurrence process of slope erosion has received widespread attention. Slope erosion in the red soil erosion area of southern China is mainly caused by slope runoff erosion. When the rainfall intensity is greater than the infiltration capacity of the soil and the water content of the soil above the interface is saturated, the excess precipitation forms surface runoff. The slope flow interacts with the soil to produce soil loss. This process is essentially a process of mutual transformation and transmission of energy, which is related to runoff velocity, energy, and sediment carrying capacity.

German scientist Ewald Wallny is known as "the pioneer of soil and water conservation research" [1]. As early as the late 19th century, he conducted in-depth research on factors affecting runoff and soil erosion, including slope, aspect, vegetation cover, soil type, about half a century earlier than similar studies in the United States. Because the soil erosion process involves many natural factors and long-time scales, experiments and observations have become one of the indispensable means of research. During the 1930s and 1940s, numerous research results were published from various experimental stations in the United States until the "World War II" before the United States entered the "golden age" of soil erosion research. However, these studies do not mathematically describe the
relationship between impact factors and soil erosion. Cook’s research in the United States is generally considered as the beginning of quantitative soil erosion [2]. He lists three sets of factors that affect soil erosion, including the ability of soils to be susceptible to erosion (soil erodibility), the potential for rainfall and runoff to cause soil erosion, including the effect of slope and slope length, the ability of vegetation cover to protect the eroded surface, and a detailed description of the second factor in each set of factors. In 1940, based on other people’s research data and their own experimental observations, Zingg established an exponential relationship between soil loss per unit area and slope and slope length [3]. Browning et al. modified the equation to increase soil erodibility and management factors and gave correlation factors for different soil types, rotations, and slope lengths [4]. Later, based on summarizing the application of the above equations, Musgrave sought to broaden the application area of the equation, re-evaluate the variables used in the previous equations, and increase the rainfall factor [5].

According to the above equations, it is easy to see that natural factors are directly used as variables, such as rainfall, slope or slope length. Because of the interaction of these factors on soil erosion, they are not independent of each other, so it is difficult to promote different regions, which greatly limits the application of the equation. As the factors considered in the equation are different, the definition of the factors is different, and the expression of the equations will be very different, and comparative analysis cannot be performed. In 1948, Smith and Whitt proposed a "ratio" type of soil loss estimation equation to solve the interaction between variables from a statistical point of view [6]. The product form of this dimensionless variable has actually become the prototype of the universal soil loss equation.

This study used the measured data of typical economic forest slope runoff plots in the hilly areas of the eastern Zhejiang Province, based on the universal soil loss equation, combined with the research results of Chinese scholars in China, established soil loss for the typical economic forest slopes in the study area. The prediction model is of great significance for soil erosion prediction and soil and water conservation planning in the study area.

2. Data and methods

With the large increase in experimental data, the comparability of data and the regional limitations of equations have become increasingly prominent. In order to make the soil loss equation compatible with national soil erosion observation data, the US Department of Agriculture established the National Soil and Water Loss Data Centre at Purdue University to collect and process runoff and erosion data throughout the United States for further analysis in 1954. Since 1956, the US Department of Agriculture has organized several academic seminars to coordinate existing soil loss equations and apply them to areas without soil erosion observations. In 1965, a detailed introduction to the universal soil loss equation was officially published in the form of Agricultural Manual No. 282 [7]. Its structure is given by

\[ A = R \cdot K \cdot LS \cdot C \cdot P \]

where \( A \) is soil loss, \( t/hm^2 \), \( R \) is rainfall erosivity factor, \( MJ\cdot mm / (hm^2 \cdot h) \), \( K \) is soil erodibility factor, \( t\cdot hm^2 \cdot h / (hm^2 \cdot MJ \cdot mm) \), \( LS \) is topographic factor, \( C \) is cover and management factor, \( P \) is soil and water conservation factor.

The universal soil loss equation is a mathematical model that represents the quantitative relationship between the amount of soil loss on the slope and its main influencing factors. It is mainly used to calculate the event average soil loss due to surface erosion under certain farming methods and management systems. A slope soil loss empirical model is estimated the event annual soil erosion caused by rainfall.

3. Results and discussion

3.1. Preliminary simulation
In experimental observations, soil erosion could only be caused by rainfall events that generate enough runoff to carry sediment, not all rainfall events. Therefore, this study summarized the results of other researchers' erosive rainfall standards and found that the erosive rainfall standards of exposed slopes in different regions were close to 12.0 mm, and the maximum rainfall intensity standards of 30 minutes were significantly different, which may be mainly related to the rainfall characteristics of different regions. According to these research results, the erosive rainfall standard in the study area was 12.0 mm, the maximum 30-minute rainfall intensity was 10 mm/h. In other words, when a rainfall (two rainfall events were more than 6 hours, otherwise it was counted as a rainfall event) exceeded 12.0 or the maximum 30-min rainfall intensity was more than 10 mm/h, the statistical analysis was carried out as an erosive rainfall event.

| Regions         | Plots          | Rainfall standard (mm) | I$_{30}$ Standard | References |
|-----------------|----------------|------------------------|-------------------|------------|
| Northwest China | Zizhou County  | 12.0                   | 13.3              | [8]        |
| Northeast China | Keshan County  | 11.6                   | 7.6               | [9]        |
| Southwest China | Bijie City     | 11.6                   | 10.2              | [10]       |
| East China      | Dean County    | 11.4                   | 10.0              | [11]       |

Brown's and Foster's [12] methods for calculating the erosivity of secondary rainfall were high accuracy and physical significance. Specific formulas for calculating the erosivity of secondary rainfall were as follows:

\[ R = \frac{E}{I_{30}} \]

\[ E = \sum_{r=1}^{n} (e_r \cdot p_r) \]

\[ e_r = 0.29[1 - 0.72 \exp(-0.082i)] \]

Where, \( R \) is the rainfall erosion force generated by a single rainfall, in unit of MJ·mm/(hm$^2$·h), \( E \) is the total kinetic energy of a rainfall, in unit of MJ/hm$^2$, \( I_{30} \) refers to the maximum rainfall intensity of 30 min in the process of a rainfall, the unit of mm/h, \( p_r \) is the rainfall in the period of \( r \), the unit of mm, \( e_r \) is the unit rainfall kinetic energy of each period, the unit of MJ/(hm$^2$·mm), \( i_r \) is the rainfall intensity during the period of \( r \), the unit of mm/h. \( r \) refers to the rainfall process with the same rainfall intensity, and the value is 1, 2, ..., \( n \) is the total number of segments divided by rainfall intensity during a rainfall process.

Sharply and Williams [13] provided another soil loss prediction model, the Erosion/Productivity Impact Model (EPIC). The soil erodibility \( K \) value in this model was determined by common physicochemical properties, and it was very convenient and widely applicable. At the same time, the method was applied in the project of calculating, analyzing and mapping soil erodibility factors in the first national water conservancy census, the national soil and water conservation census. Therefore, the calculation formula of soil erodibility \( K \) in the EPIC model was also used in this study. The specific calculation process was as follows:

\[ K = 0.1317 \cdot P_0 \cdot P_1 \cdot P_2 \cdot P_3 \]

\[ P_0 = \left[ \frac{Sil}{Cla + Sil} \right]^{0.3} \]

\[ P_1 = 1.0 - 0.25 \cdot C \left[ \frac{1}{C + e^{(3.72 - 2.95C)}} \right] \]

\[ P_2 = 1.0 - 0.7 \cdot Sn \left[ \frac{1}{Sn + e^{(-5.51 + 22.95Sn)}} \right] \]

\[ P_3 = 0.2 + 0.3 \cdot e^{(-0.0256Sn - 1.5 - 0.002mm)} \]

Where, \( K \) is the soil erodibility, the unit of t·hm$^2$·h/(hm$^2$·MJ·mm), \( San \) is the percentage of sand content (2-0.05 mm), \( Sil \) represents the percentage of silt content (0.05-0.002 mm), \( Cla \) is the
percentage of viscosity (<0.002mm), C is the percentage of organic carbon content, \( C = 0.58 \times \text{organic matter (\%)} \), \( S_n = 1 - \frac{San}{100} \).

Liu [14] conducted experimental research and believed that the slope surface of uniform slope in China was calculated by subsection function. According to the slope characteristics of the field observation community in the study area, the slope length was mainly concentrated in 20m, and the slope was above 10 degrees. Therefore, the formulas of topographic factors when slope length is greater than 10 m and the slope angle is greater than 10 degrees was selected as follows:

\[
L_S = \left( \frac{\lambda}{22.13} \right)^{\frac{\pi}{2}} \times (21.91 \cdot \sin \theta - 0.96)
\]

Liu [14] decomposed the C factor into the product of two sub-factors, namely, the product of canopy covers sub-factor \( C_c \) and ground cover sub-factor \( C_s \). According to the specific situation of the study and the measurement of vegetation coverage, the calculation method of factor C of forest land proposed by Liu was used for vegetation coverage and management factors. The specific calculation method was as follows:

\[
C = C_c \cdot C_s
\]

\[
C_c = 0.988 \cdot e^{(-0.11V_c)}
\]

\[
C_s = 1.029 \cdot e^{(-0.0235V_r)}
\]

Where, \( C_c \) and \( C_s \) are canopy cover sub-factors and ground cover sub-factors, respectively, \( V_c \) and \( V_r \) are canopy coverage (\%) and surface coverage (\%), respectively.

In this study, the slope of tea runoff plot was planted in contour zone, and the other plots did not adopt any soil and water conservation measures. Therefore, the soil and water conservation factor \( P \) was one, while the slope of tea lands have exceeded twenty-five degrees, so the \( P \) value was also one.

Preliminary simulation results showed that the simulation accuracy of different types of economic forests was poor, and the Nash efficiency coefficients were even negative. Therefore, the actual situation of the study was further combined. The soil erodibility factor \( K \), terrain factor \( L_S \) and soil and water conservation measures factor \( P \) were relatively fixed. Hence, based on the optimization of rainfall erosion force factor \( R \) and vegetation cover and management factor \( C \), the rainfall erosion force \( R \) and vegetation cover and management factor \( C \) were adjusted under the basic framework of the soil loss equation \((A = R \cdot K \cdot L \cdot S \cdot C \cdot P)\).

Table 2. Unoptimized universal soil loss equation simulation accuracy index

| Forest land type | Coefficient of determination | Nash efficiency coefficient |
|------------------|------------------------------|-----------------------------|
| Cherry blossom   | 0.1599                       | -111.7456                   |
| Bamboo forest    | 0.8522                       | -17.4085                    |
| Tea              | 0.9463                       | -2.3486                     |
| Cherry           | 0.8116                       | -112.9347                   |
| Arbutus          | 0.4127                       | -43.0132                    |

3.2. Model optimization and verification

There were differences in rainfall characteristics in different regions. Therefore, the soil loss A, the soil erodibility factor \( K \), the topographic factor \( L_S \), the vegetation cover factor \( C \), and the soil and water conservation factor \( P \) were used to generate the event rainfall erosivity factor \( R_e = A / K \cdot L \cdot S \cdot C \cdot P \). The result was statistically regressive analyzed with the calculation \( R \) of the Brown and Foster formulas, and the regression equations of different experimental regions were obtained finally.
Figure 1. Regression relationship of rainfall erosivity in the typical study area

In general, the relationship between the Re of the economic forest rainfall erosivity and the R of the formula in the Yuyao city was a power function relationship. The equation was \( R_e = 0.004 \cdot R^{1.594} \), the coefficient of determination was 0.8290, and the Nash efficiency coefficient was 0.8285. The fitting effect was ideal.

Through the optimization of the universal soil loss equation, the soil and water loss prediction model of the economic forest in the low mountainous area of eastern Zhejiang was finally obtained: \( A=0.004 \cdot R^{1.594} \cdot K \cdot L \cdot S \cdot C_c \cdot C_s \cdot P \). Comparing the simulation results of different economic forest equations, it was found that the optimized soil loss equation to simulate the soil loss of typical economic forests in the low mountainous areas of eastern Zhejiang is significantly improved than that of the universal soil loss equation directly. Further calculating the accuracy index of the two simulation results, it was found that the Nash efficiency coefficient of the simulation results of the universal soil loss equation was far less than one, indicating that the results were not credible. The direct use was not suitable for predicting the soil erosion of typical economic forest land in the study area. The Nash efficiency coefficient of the universal soil loss equation simulation result was above 0.80, and the determined coefficient of the measured value was above 0.85, indicating that the result was credible. Therefore, according to the characteristics of the main runoff process in the study area, which was full of runoff, high vegetation coverage and structural compounding, adjusting the rainfall erosivity factor and vegetation cover factor could greatly improve the applicability of the universal soil loss equation.

Table 3. Soil loss equation simulation accuracy index

| Plots      | Original general equation | Optimized general equation |
|------------|---------------------------|----------------------------|
|            | Coefficient of determination | Nash efficiency coefficient | Coefficient of determination | Nash efficiency coefficient |
| Cherry blossom | 0.1599 | -111.7456 | 0.8528 | 0.8047 |
| Bamboo     | 0.8522 | -17.4085  | 0.9939 | 0.9909 |
| Tea        | 0.9463 | -2.3486   | 0.9897 | 0.9867 |
| Cherry     | 0.8116 | -112.9347 | 0.9162 | 0.9018 |
| Arbutus    | 0.4127 | -43.0132  | 0.9794 | 0.9770 |
4. Conclusion
In consideration of the characteristics of the runoff in the study area, the prediction model for soil loss in the hilly areas of the eastern Zhejiang Province is proposed as:

\[ A = 0.004 \cdot R^{1.594} \cdot K \cdot L \cdot S \cdot C_c \cdot C_s \cdot P. \]

According to the model simulation results, the simulation accuracy of soil loss equation on different economic forest lands is above 0.80, which can meet the forecasting requirements. However, for continuous rains or short-duration rainstorms, there is a certain deviation in the simulated values.

In general, under the framework of the universal soil loss equation, the factors of the study area are combined to correct the factors, which can better simulate the soil loss on the slope.

Acknowledgments
This research was funded by the Hydraulic Technological Program of Zhejiang Province (RB1609) and Science and Technology Planning Project of Zhejiang Province(2018F10030). The authors are grateful to the editor and the reviewers for their excellent work.

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