

# Multiple Statistical Models Based Analysis of Causative Factors and Loess Landslides in Tianshui City, China

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**Abstract.** Tianshui City is one of the mountainous cities that are threatened by severe geo-hazards in Gansu Province, China. Statistical probability models have been widely used in analyzing and evaluating geo-hazards such as landslide. In this research, three approaches (Certainty Factor Method, Weight of Evidence Method and Information Quantity Method) were adopted to quantitatively analyze the relationship between the causative factors and the landslides, respectively. The source data used in this study are including the SRTM DEM and local geological maps in the scale of 1:200,000. 12 causative factors (i.e., altitude, slope, aspect, curvature, plan curvature, profile curvature, roughness, relief amplitude, and distance to rivers, distance to faults, distance to roads, and the stratum lithology) were selected to do correlation analysis after thorough investigation of geological conditions and historical landslides. The results indicate that the outcomes of the three models are fairly consistent.

## 1. Introduction

Tianshui, a city in the southeastern part of Gansu Province, located in the south of the Longzhong Loess Plateau and north of the Qinling Mountains. The Weihe River and its tributaries cross through the Tianshui City from west to east. Thus, Tianshui City has a typical valley basin landform. Special geological conditions in the region lead to frequent geological disasters. Historically, geological disasters have caused serious casualties and economic losses. For example, on July 12, 1978, the rainstorm in Bo Yang caused a number of loess landslides, debris flow. Not only killed 7 people, but also buried Baiyang railway station and interrupted Baotian railway traffic 360h [1]. In the autumn of 1984, rainfall triggered 88 landslides in the Tianshui City and its surrounding areas, railways and highways were seriously threatened [2]. On August 11, 1990, rainstorm in Tianshui City induced dozens of landslides, 22 people were killed, and 7 of whom were killed by one landslide. Besides, in Qinzhou District, Jiaoshuwan landslide, Taishanmiao landslide deformed intensively threatened lives and property of 7,780 citizens [3]. From June 19 to July 26, 2013, a total of four heavy rainstorms in Tianshui area led to extensive geological disasters which resulted in 24 deaths [4]. The landslides in Dagou on July 21 [5], Yushu Village on July 29 [4], and Caowang village on July 29 [6] are all typical loess landslide caused by this round of heavy rainstorms.

Due to the lack of detailed landslide cataloging and high accuracy of the data, studies regarding spatial correlation of the loess landslide and the disaster factors of Tianshui City are rare. With the development of 3S (GIS, GPS and RS) technology, spatial correlation of landslide and causative



factors based on statistics and probability analysis is becoming well developed. Various approaches and models have been proposed and popularized, such as certainty factor (CF) [7], weights-of-evidence (WOE) method [8], information quantity (I) method [9], conditional probability method [10] and so forth. Therefore, investigation of loess landslide in Tianshui City area (Qinzhou District and Maiji District) using statistical models (i.e., certainty factor (CF) method, weights-of-evidence (WOE) method, and information quantity method (I)) is of great theoretical and practical significance to further understand the formation mechanism of landslides and carry out effective risk assessment in this area. It will complement and improve the current relevant studies in the Tianshui City area, as well as providing scientific basis and technical support on landslide hazard prevention and management decision-making.

## 2. Method

From the spatial scale, research on landslide hazard could be divided into regional studies and monomer studies. Regional studies mainly focus on the analysis of causative factors, susceptibility, risk, and risk assessment of the landslide hazard in specific areas. All these analysis were actually based on the correlation of landslide in the study area and causative factors. Therefore, analysis of potential causative factors is the key to evaluate the success or failure of landslide susceptibility and hazard risk.

### 2.1. Certainty factor method

Certainty Factor method [7] used as a probability function for landslide hazard analysis. The basic assumption is that the landslide will occur in the future if the geological conditions of a certain area are the same or similar to those of the landslide in the past, which could be shown as:

$$CF = \left\{ \begin{array}{ll} \frac{PP_a - PP_s}{PP_s(1 - PP_s)} & \text{if } PP_a \geq PP_s \\ \frac{PP_a - PP_s}{PP_s(1 - PP_a)} & \text{if } PP_a < PP_s \end{array} \right\} \dots\dots\dots(1)$$

Where, in the formula (1),  $PP_a$  is the conditional probability of occurrence of event (landslide) in data class a, which can be expressed as the ratio of landslide area to unit area in the unit representing data class a when the landslide is applied.  $PP_s$  is the prior probability of occurrence of the event throughout the study area A and can be expressed as the ratio of landslide area to study area in the whole study area.

CF value change in the interval of [-1, 1]. If CF value is positive, representing the event of deterministic growth, that is, the landslide occurrence of certainty. In other words, this unit is prone to be a landslide area. While negative CF value represents the certainty of reduction, that is, the certainty of landslide occurrence is low (not prone to landslides). If CF value is close to 0, which means the prior probability and the conditional probability are very close (the certainty of event occurrence cannot be determined). In short, the unit cannot determine whether or not it is a landslide prone area.

Using the spatial analysis module of ArcGIS 10, the number of landslide units and the number of factor units in all the factors were calculated, and the CF values of the factor layers were calculated, subsequently.

According to Eq. (2), the influence and susceptibility of each factor to landslide are calculated.

$$S_{CF} = CF_{(i,max)} - CF_{(i,min)} \dots\dots\dots(2)$$

Where,  $S_{CF}$  is overall susceptibility of the landslide index for each factor.  $CF_{(i,max)}$  is the maximum value of the certainty factor of landslide for each factor  $i$ ;  $CF_{(i,min)}$  is the minimum value of the certainty factor of landslide for each factor  $i$ . The higher the  $S_{CF}$ , the higher probability of the response and susceptibility of the factor to the landslide.

### 2.2. Weights-of-evidence method

Based on the Bayesian statistical model, Weights-of-evidence method is originally applied in the evaluation of mineral resources reserves in earth science [11]. In recent years, this method has been widely used in landslide susceptibility evaluation [12]. In Landslide hazard susceptibility and risk

mapping, weight of evidence method is be used to calculate the weight for each landslide causative factors based on the two cases of landslides (i.e., existence and absence). The basic assumptions of this approach are: 1) the conditions of future landslides are similar to those that favor landslide occurrence in the past; and 2) the causative factors for landslide mapping do not change with time.

According to the Bayesian rule, the probability of occurrence of landslide and the conditional probability function expressed by equation (3) under the condition of evidence factor F:

$$P\{L|F\} = \frac{P\{L \cap F\}}{P\{F\}} = \frac{N\{L \cap F\}}{N\{F\}} \dots\dots\dots (3)$$

Namely, 
$$P\{F|L\} = \frac{P\{L \cap F\}}{P\{L\}} = \frac{N\{L \cap F\}}{N\{L\}} \dots\dots\dots (4)$$

Formula (5), (6) and (7) are used to calculate the evidence of landslide occurrence.  $P\{F|L\}/P\{F|\bar{L}\}$  represents the adequacy of landslide occurrence;  $P\{\bar{F}|L\}/P\{\bar{F}|\bar{L}\}$  represents the necessary rate of landslide occurrence.  $W^+$  indicates the probability of a landslide at the current causative factor level, and the size indicates the positive correlation between the causative factor level and the landslide.  $W^-$  represents the probability of a landslide occurring outside of the causative factor level, which represents the negative correlation coefficient of the landslide within the causative factor level. The difference ( $W_c$ ) represents the weight of the landslide within the causative factor level.

$$W_i^+ = \ln \left( \frac{P\{F|L\}}{P\{F|\bar{L}\}} \right) \quad (5) \quad W_i^- = \ln \left( \frac{P\{\bar{F}|L\}}{P\{\bar{F}|\bar{L}\}} \right) \quad (6) \quad W_c = W_i^+ - W_i^- \quad (7)$$

The following formulas (8) and (9) are given by the formulas (5) and (6):

$$W_i^+ = \ln \left( \frac{\frac{N_1}{N_1 + N_2}}{\frac{N_3}{N_3 + N_4}} \right) \dots\dots\dots (8) \quad W_i^- = \ln \left( \frac{\frac{N_2}{N_1 + N_2}}{\frac{N_4}{N_3 + N_4}} \right) \dots\dots\dots (9)$$

Where  $N_1$  represents the number of grids in which the landslide occurred within the stage of the factors;  $N_2$  represents the number of grids that landslide occurred outside the stage of the factors;  $N_3$  represents the number of grids that landslide did not occurred within the stage of the factors; and  $N_4$  represents the number of grids that landslide did not occurred outside the stage of the factors.

The weight ( $W_c$ ) reflects the importance of the factor to the landslide. Positive total weight indicates that the level is favorable for the occurrence of the landslide, while negative total weight indicates that it is not conducive to the occurrence of the landslide. The correlation of landslides is very small if total weight is close to 0.

Using the spatial analysis module of ArcGIS 10, the number of landslide units and the number of factor units of all grades in each factor as well as  $W^+$ ,  $W^-$  and  $W_c$  were calculated.

According to Eq. (10), the influence and susceptibility of each factor to landslide are calculated.

$$S_W = W_{(i,\max)} - W_{(i,\min)} \quad (10)$$

Where,  $S_W$  is the overall susceptibility index of the landslide for each factor;  $W_{(i,\max)}$  is the maximum value of weights-of-evidence for each category of factor  $i$ ;  $W_{(i,\min)}$  is the minimum value of weights-of-evidence for each factor  $i$ . The higher the  $S_W$ , the higher probability of the response and susceptibility of the factor to the landslide.

### 2.3. Information quantity method

The information quantity method <sup>[9]</sup> assumed that the occurrence of landslide hazards correlated with the amount of information obtained during forecast. Equation of the amount of information  $I(H, x_i)$  provided by each factor  $x_i$  to the landslide occurrence event ( $H$ ) can be seen below:

$$I(H, x_i) = \ln \frac{P(H|x_i)}{P(H)} = \ln \frac{N_i/S_i}{N/S} = \ln \frac{N_i/N}{S_i/S} \quad (11)$$

Where  $I(H, x_i)$  is the information value of the unit,  $P(H|x_i)$  is the probability of occurrence of landslides in the condition  $x_i$ ,  $P(H)$  is the probability of landslides in the study area,  $S$  is the total number of landslides in the study area,  $N$  is the total number of landslide units,  $S_i$  is the evaluation area Factor  $x_i$ ,  $N_i$  is the number of landslide units distributed within the factor  $x_i$ .

Using the spatial analysis module of ArcGIS 10, the number of landslide units, the number of factor units of all grades in each factor, and the I value of each factor were calculated.

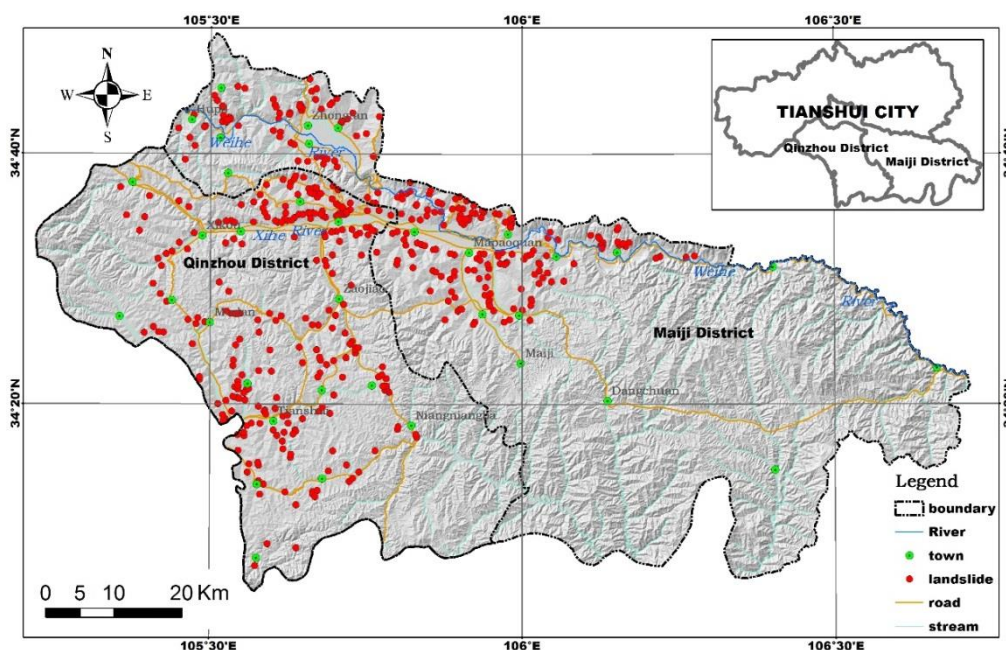
The influence and susceptibility of each factor to landslide were calculated using equation (12) below:

$$S_I = I_{(i, \max)} - I_{(i, \min)} \quad (12)$$

Where  $S_I$  is the overall susceptibility index of the landslide for each factor;  $I_{(i, \max)}$  is the maximum value of the landslide information value for each category of factor  $i$ ;  $I_{(i, \min)}$  is the minimum value of landslide information for each factor  $i$ . The higher the  $S_I$ , the higher probability of the response and susceptibility of the factor to the landslide.

### 3. Study area

The study area, Tianshui City, is located in southeastern Gansu Province. The geographical location of Tianshui City is: longitude 105°13'15" ~ 106°42'58" E, latitude 34°5'5" ~ 34°49'40" N with a total population of 1.3 million and a total area of about 5,833 km<sup>2</sup>. The area of the two major districts of Tianshui City (i.e., Qinzhou and Maiji District) is about 2349 km<sup>2</sup> and 3484 km<sup>2</sup>, respectively (Figure 1). The population density is around 223 person / km<sup>2</sup>. Tianshui is a typical populous city with fragile geological environment. Tianshui City is a high incidence area of landslide disaster, which seriously threatens people's life and property safety.



**Figure 1.** The location of the research area and the distribution of landslides in study area.

### 4. Data preparation

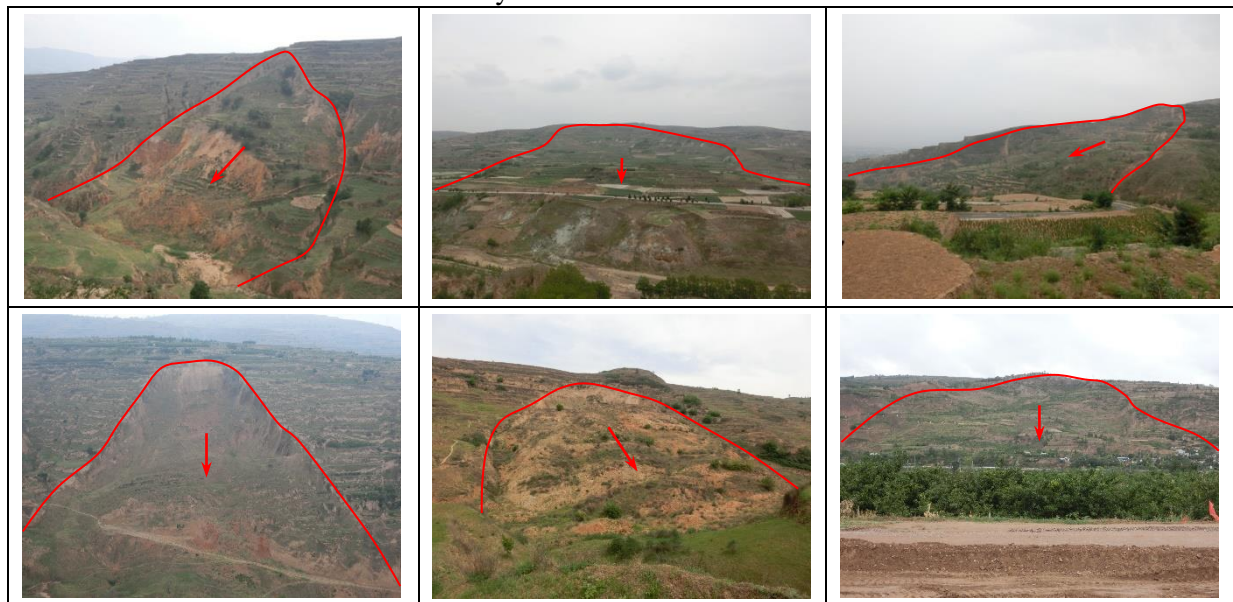
The data used in this study including detailed landslide inventory and high-accuracy causative factors data. Landslide inventory were obtained from existing documents, remote sensing images and field surveys. High-accuracy causative factors data were derived from SRTM DEM data at 30m resolution,



1: 200,000 regional geological map and google earth. The characteristics and causes of loess landslide disasters in the study area were identified after systematic summary and investigation. Causative factors of landslide development were selected based on identified characteristics and origin. The above typical middle - scale landslides with area greater than  $10,000\text{m}^2$  and landslide length greater than 100 m in the study area is emphasized.

#### 4.1. Landslide inventory

A detailed and reliable database of landslide spatial distribution in the study area was established by means of analysis and discrimination of existing landslide hazard research data, interpretation of remote sensing images and verification of field investigation. The data of 475 landslide hazard points were acquired, including 257 in Qinzhou District and 218 in Maiji District (Figure 2). In the study area, the area of 470 landslides are larger than  $10,000\text{ m}^2$ , accounting for 99% of all landslides. In general, the selected landslide hazards meet the requirements of sampling. The total landslide hazard area is  $89\text{ km}^2$ , and the landslide vector map is converted to raster at a grid size of  $30\text{m} \times 30\text{m}$ . A total of 6,481,583 grid cells were obtained after rasterization with 98,968 landslide grid cells which took around 1.5% of the total area. The density of the landslide is  $0.1/\text{km}^2$ .



**Figure 2.** Pictures of the typical landslides in study area.

#### 4.2. Data of environmental factors

A total of 12 causative factors were categorized into three classes (i.e., geomorphological factors, geological factors, and human activity factors) selected in this study. Geomorphological factors are altitude, slope, aspect, curvature, plan curvature, profile curvature, roughness, relief amplitude and distance to rivers (Figure 3a-3h). The geological factors include distance to faults, and the stratum lithology; and human activity factor is the distance to roads (Figure 4a-4d). The geomorphological factors were obtained from DEM data of 30m resolution in the study area by using ArcGIS software. The geological factors are based on 1: 200,000 regional geological map, using GIS tools to transform the raster data. Human activity factors were subsequently obtained through the google earth map, and then use ArcGIS 10 software to do more processing and statistical analysis (Table 1).

## 5. Results and discussion

#### 5.1. Susceptibility analysis of landslide and classification factors

According to the data of the landslide and the cause of disaster in the study area, the CF,  $W_c$ , and I of the grading factor layers in the 12 factors were calculated, respectively. From the results in Table 2, among the 12 landslide causative factors in the region, 1200m ~ 1400m above sea level,  $10^\circ \sim 15^\circ$

slope, southwest slope,  $-0.5 \sim 0.5$  curvature,  $-0.5 \sim 0.5$  plan curvature,  $-0.5 \sim 0.5$  profile curvature,  $1 \sim 1.05$  roughness,  $60 \sim 120$  m relief amplitude, Quaternary Upper Pleistocene ( $Q_3$ ) Malan loess and Neogene (N) mudstones in the stratum lithology,  $4000\text{m} \sim 5000\text{m}$  away from the fault,  $1200\text{m} \sim 1600\text{m}$  away from the river and  $500\text{m} \sim 1500\text{m}$  away from the road are the advantage factor interval of the loess landslide hazard.

**Table 1.** Loess landslides 12 causative factors of Tianshui City

Data source	Factors	Classification of factors
<b>SRTM DEM in the resolution of 30m</b>	Altitude	$<1000$ m、 $1000 \sim 1200$ m、 $1200 \sim 1400$ m、 $1400 \sim 1600$ m、 $1600 \sim 1800$ m、 $1800 \sim 2000$ m、 $2000 \sim 2200$ m、 $2200 \sim 2400$ m、 $>2400$ m
	Slope	$0 \sim 5^\circ$ 、 $5 \sim 10^\circ$ 、 $10 \sim 15^\circ$ 、 $15 \sim 20^\circ$ 、 $20 \sim 25^\circ$ 、 $25 \sim 30^\circ$ 、 $30 \sim 35^\circ$ 、 $35 \sim 40^\circ$ 、 $>40^\circ$
	Aspect	Flat, north、Northeast, Southeast, South, South West, West, North West
	Curvature	$<-4$ 、 $-4 \sim -2$ 、 $-2 \sim -0.5$ 、 $-0.5 \sim 0$ 、 $0 \sim 0.5$ 、 $0.5 \sim 2$ 、 $2 \sim 4$ 、 $>4$
	Plan curvature	$<-2$ 、 $-2 \sim -1$ 、 $-1 \sim -0.5$ 、 $-0.5 \sim 0$ 、 $0 \sim 0.5$ 、 $0.5 \sim 1$ 、 $1 \sim 2$ 、 $>2$
	Profile curvature	$<-2$ 、 $-2 \sim -1$ 、 $-1 \sim -0.5$ 、 $-0.5 \sim 0$ 、 $0 \sim 0.5$ 、 $0.5 \sim 1$ 、 $1 \sim 2$ 、 $>2$
	Roughness	$1 \sim 1.05$ 、 $1.05 \sim 1.1$ 、 $1.1 \sim 1.15$ 、 $1.15 \sim 1.2$ 、 $1.2 \sim 1.25$ 、 $1.25 \sim 1.3$ 、 $1.3 \sim 1.35$ 、 $1.35 \sim 1.4$ 、 $>1.4$
	Relief amplitude	$<30$ m、 $30 \sim 60$ m、 $60 \sim 90$ m、 $90 \sim 120$ m、 $120 \sim 150$ m、 $150 \sim 180$ m、 $180 \sim 210$ m、 $210 \sim 240$ m、 $>240$ m
	Distance to rivers	$<400$ m、 $400 \sim 800$ m、 $800 \sim 1200$ m、 $1200 \sim 1600$ m、 $1600 \sim 2000$ m
	Stratum lithology	Quaternary Holocene ( $Q_4$ ), Quaternary Upper Pleistocene ( $Q_3$ ), Neogene (N), Paleogene (E), Jurassic (J), Carboniferous (C), Devonian (D), Paleozoic ( $P_{Z1}$ ), Sinian (Z), anterior Sinian (AnZ), granite, diorite ( $\gamma$ )
<b>1: 200,000 regional geological map</b>	Distance to faults	$<1000$ m、 $1000 \sim 2000$ m、 $2000 \sim 3000$ m、 $3000 \sim 4000$ m、 $4000 \sim 5000$ m、 $5000 \sim 6000$ m、 $6000 \sim 7000$ m、 $7000 \sim 8000$ m、 $>8000$ m
	Distance to roads	$<500$ m、 $500 \sim 1000$ m、 $1000 \sim 1500$ m、 $1500 \sim 2000$ m、 $2000 \sim 2500$ m、 $2500 \sim 3000$ m、 $>3000$ m
<b>Google earth images</b>	Distance to roads	$<500$ m、 $500 \sim 1000$ m、 $1000 \sim 1500$ m、 $1500 \sim 2000$ m、 $2000 \sim 2500$ m、 $2500 \sim 3000$ m、 $>3000$ m

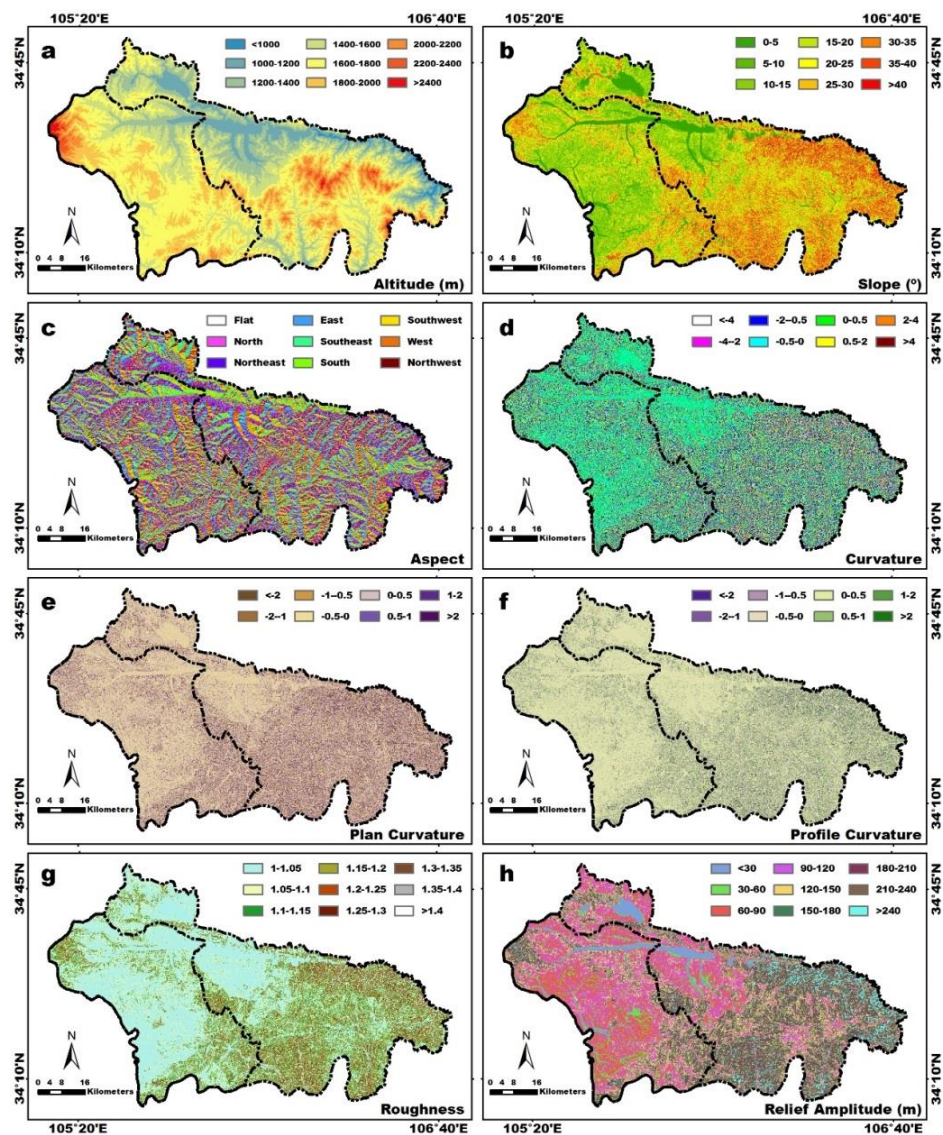


Figure 3. The grading map of various geomorphological factors in the study area.

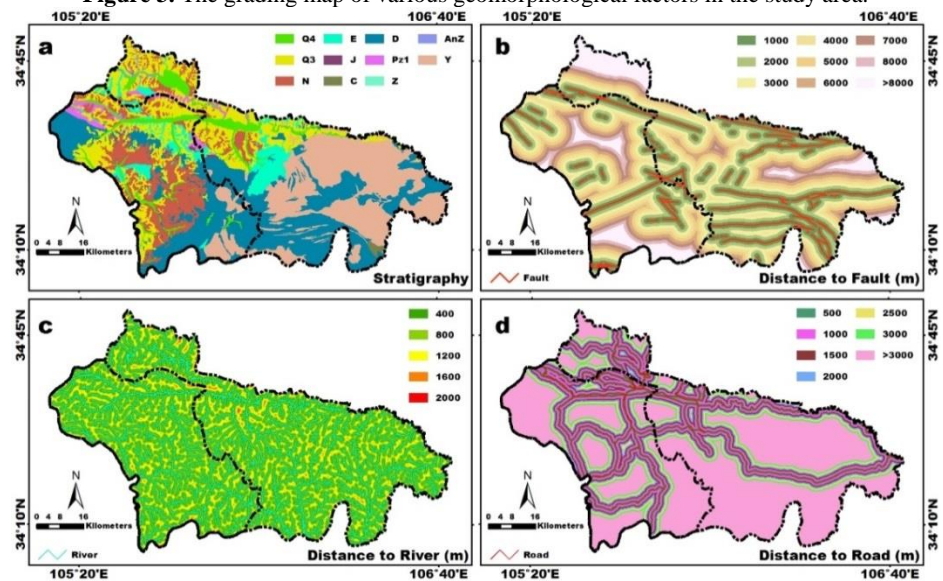


Figure 4. The grading map of various geological factors in the study area.



**Table 2.** Statistics of 12 causative factors of loess landslide in Tianshui City

<b>Factors and its grades</b>	<b>CF</b>	<b>W<sub>c</sub></b>	<b>I</b>	<b>Factors and its grades</b>	<b>CF</b>	<b>W<sub>c</sub></b>	<b>I</b>
<b>Altitude</b>				<b>Slope</b>			
1: <1000	-0.97	-3.59	-3.57	1: 0-5	-0.26	-0.32	-0.30
2: 1000-1200	0.40	0.56	0.50	2: 5-10	0.48	0.76	0.64
3: 1200-1400	0.69	1.56	1.13	3: 10-15	0.51	0.96	0.71
4: 1400-1600	0.16	0.22	0.17	4: 15-20	0.31	0.46	0.36
5: 1600-1800	-0.40	-0.69	-0.50	5: 20-25	-0.34	-0.47	-0.41
6: 1800-2000	-0.94	-2.97	-2.78	6: 25-30	-0.71	-1.35	-1.23
7: 2000-2200	-1			7: 30-35	-0.82	-1.79	-1.68
8: 2200-2400	-1			8: 35-40	-0.86	-2.00	-1.93
9: >2400	-1			9: >40	-0.90	-2.38	-2.34
<b>Aspect</b>				<b>Roughness</b>			
1: Flat	-0.70	-1.21	-1.20	1: 1-1.05	0.42	1.31	0.53
2: North	0.10	0.12	0.10	2: 1.05-1.1	-0.14	-0.19	-0.14
3: Northeast	-0.16	-0.20	-0.18	3: 1.1-1.15	-0.70	-1.30	-1.18
4: East	-0.31	-0.41	-0.36	4: 1.15-1.2	-0.80	-1.71	-1.62
5: Southeast	-0.29	-0.38	-0.34	5: 1.2-1.25	-0.84	-1.89	-1.83
6: South	0.15	0.18	0.16	6: 1.25-1.3	-0.87	-2.08	-2.04
7: Southwest	0.20	0.25	0.21	7: 1.3-1.35	-0.90	-2.27	-2.25
8: West	0.09	0.10	0.09	8: 1.35-1.4	-0.90	-2.27	-2.25
9: Northwest	0.16	0.20	0.17	9: >1.4	-0.92	-2.58	-2.56
<b>Curvature</b>				<b>Plan curvature</b>			
1: <-4	-0.89	-2.17	-2.15	1: <-2	-0.91	-2.43	-2.41
2: -4--2	-0.82	-1.73	-1.69	2: -2--1	-0.78	-1.57	-1.52
3: -2--0.5	-0.15	-0.21	-0.16	3: -1--0.5	-0.34	-0.46	-0.41
4: -0.5-0	0.29	0.49	0.34	4: -0.5-0	0.24	0.44	0.26
5: 0-0.5	0.26	0.39	0.30	5: 0-0.5	0.20	0.34	0.21
6: 0.5-2	-0.28	-0.41	-0.32	6: 0.5-1	-0.45	-0.67	-0.60
7: 2-4	-0.82	-1.73	-1.69	7: 1-2	-0.78	-1.57	-1.52
8: >4	-0.91	-2.37	-2.35	8: >2	-0.92	-2.56	-2.54
<b>Profile curvature</b>				<b>Distance to roads</b>			
1: <-2	-0.86	-2.00	-1.99	1: <500	0.40	0.59	0.50
2: -2--1	-0.75	-1.41	-1.36	2: 500-1000	0.62	1.15	0.94
3: -1--0.5	-0.45	-0.65	-0.59	3: 1000-1500	0.60	1.07	0.90
4: -0.5-0	0.20	0.35	0.22	4: 1500-2000	0.49	0.75	0.66
5: 0-0.5	0.23	0.43	0.26	5: 2000-2500	-0.06	-0.06	-0.06
6: 0.5-1	-0.36	-0.50	-0.45	6: 2500-3000	-0.11	-0.12	-0.11
7: 1-2	-0.75	-1.42	-1.37	7: >3000	-0.79	-2.17	-1.54
8: >2	-0.86	-1.97	-1.95				
<b>Relief amplitude</b>				<b>Distance to faults</b>			
1: <30	-0.55	-0.82	-0.79	1: <1000	-0.07	-0.09	-0.07
2: 30-60	0.44	0.63	0.58	2: 1000-2000	-0.10	-0.12	-0.10
3: 60-90	0.50	0.94	0.68	3: 2000-3000	0.12	0.16	0.13
4: 90-120	0.45	0.82	0.58	4: 3000-4000	0.16	0.19	0.17
5: 120-150	-0.31	-0.44	-0.37	5: 4000-5000	0.34	0.46	0.40



6: 150-180	-0.73-1.42 -1.29	6: 5000-6000	0.01	0.02	0.01
7: 180-210	-0.86-2.06 -1.94	7: 6000-7000	-0.17	-0.20	-0.18
8: 210-240	-0.92-2.68 -2.60	8: 7000-8000	-0.74	-1.40	-1.35
9: >240	-0.98-3.79 -3.73	9: >8000	-0.16	-0.18	-0.17
<b>Stratum lithology</b>		<b>Distance to rivers</b>			
1: Q <sub>3</sub>	0.59 1.31 0.87	1: <400	-0.08	-0.16	-0.08
2: E	-0.08-0.09 -0.08	2: 400-800	-0.00	-0.00	-0.00
3: N	0.67 1.47 1.08	3: 800-1200	0.11	0.13	0.11
4: D	-0.95-3.42 -3.08	4: 1200-1600	0.71	1.26	1.19
5: P <sub>z1</sub>	-0.28-0.34 -0.33	5: 1600-2000	-0.92	-2.47	-2.45
6: Y	-1.00-6.11 -5.80				
7: AnZ	0.58 0.88 0.85				
8: J	-1				
9: Q <sub>4</sub>	-0.10-0.11 -0.10				
10: C	-1				
11: Z	-0.65-1.04 -1.03				

In the altitude layer, the value which the interval between 1200m and 1400m is the highest, that is obviously higher than other grades, which implies that the factor level between 1200m and 1400m is the advantage interval of landslide development. The bedrock areas for hard rock distributed that the elevation is higher, where are not prone to landslides. The results are in accordance with the results of [12].

In the slope gradient factor layer, the value of the interval between 5° and 20° are all greater than 0, which indicates that this slope range is sensitive to the landslide, which is in accordance with the research of (Wu et al. 2006; 2014) [1], [6]. Besides, the value of 10° ~ 15° in the factor layer is the highest, which is significantly higher than other grades. It shows that the slope of 10° ~ 15° is extremely sensitive to the development of medium-scale landslides.

In the aspect layer, the value of southwest direction is the highest, while the northwest direction is the second highest. The two factor layers are the prone layer of the landslide. The slope aspect determines the hours of receiving sunshine and the intensity of solar radiation, which influences the soil moisture content, the degree of weathering and fragmentation of rock, soil, and the vegetation coverage, thus affecting the formation of landslide.

Regarding all the curvature, plan curvature and profile curvature of the three curvature factors, -0.5 ~ 0.5 factor intervals are prone to factor layer. Further analysis showed that the -0.5 ~ 0 interval of the curvature -0.5 ~ 0 of the plan curvature and the 0 ~ 0.5 interval of the profile curvature are the most sensitive intervals. The curvature of the three groups unanimously reveals the upward concave. The susceptibility of the element to the landslide, i.e., the concave type slope, greatly dominated the development of the landslide above medium scale.

In the roughness layer, the range of 1 to 1.05 is the only positive value interval, which revealed it's the control effect on the landslide in study area. But 1 ~ 1.05 is the lowest in the roughness layer, which indicates that the variation of surface fluctuation is relatively low.

In the relief amplitude factor layer, the value of the 60 ~ 120 m interval is the highest, which becomes the landslide prone area. Analyzing the most susceptible grading layer of the five kinds of factors, such as curvature, plan curvature, profile curvature, roughness and relief amplitude, the landslide prone areas are the lower relief amplitude and lower slope erosion which is closely related to the low-angle loess-mudstone interface landslide developed extensively in the study area.

In the stratum lithology factor layer, the values of the Quaternary Upper Pleistocene (Q<sub>3</sub>) Malan loess and the Neogene (N) mudstone are both greater than 1. This factor layer is most sensitive to the development of the landslide in the area, and is well consistent with the common development of the sliding-prone stratum such as the Quaternary Upper Pleistocene Malan loess and the Neogene mudstone of the in the past research.

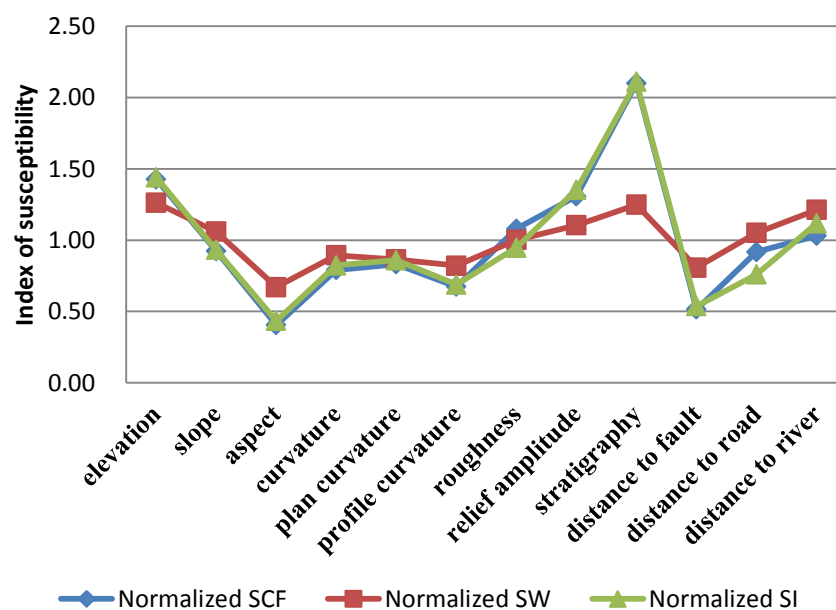
Apparently, the fault structure controls the development of landslides, especially the deep and active faults. Fracture structure leads to the concentration of ground stress, rock fragmentation, weathering enhanced, mechanical strength decreased, and active groundwater. From the buffer of fault layer, the total weight value of the buffer zone between 4000m and 5000m is the highest, which is the most sensitive interval of landslide development. Mohammady et al. (2012) [13] revealed that the closer to the fault, the more favorable is the occurrence of the landslide. But in this research, the total weight value of distance to faults between 4000m and 5000m is the most sensitive interval of landslide development. This result is similar to the results of recent researches [8], [12].

The influence of water system on the landslide is mainly caused by the strong erosion including the erosion at the slope feet, at the bank slope, changing the stress state of the slope body, softening the rock mass and so on. In the buffer of river layer, the buffer interval value between 1200m ~ 1600m is the largest, which is the dominant interval range of the landslide. In the past, Kayastha et al. (2012) [14] showed that the closer to the water system, the more favorable the landslide occurred. However, in this research, the results show that the distance from 1200m to 1600m in the buffer zone is the most sensitive to the landslide response, and not the closer to the river, the more sensitive to the landslide. This result is consistent with some other researches [8], [12].

The influence of road on landslide is mainly caused by cutting slope in highway construction, irrational drainage and frequent vibration of passing vehicles. The value of the distance between 500m and 1500m in the distance layer of the road is the largest, which is the easy-to-hit interval of the landslide. Previous studies [13], [15] suggest that the closer to the road, the more favorable is the occurrence of landslide. The results of the study show that the distance from 500m to 1500m is the most sensitive to the landslide response, and Pourghasemi et al. (2013) [8] and Regmi et al. (2010) [12] have got similar results.

### 5.2. Susceptibility analysis of landslide and integral environmental factors

It could be found from the analysis of above section that the causative factors and susceptibilities of the grading factor layers of 12 factors are different, and their respective interval of advantages can be calculated. For a certain type of factor, the influence on landslide is also different. In this paper, we try to use the S value of landslide susceptibility index to represent the extent of influence of 12 factors on landslide development. According to Eq. (2), Eq. (10) and Eq. (12), the susceptibility index S of the whole 12 factors are calculated, and the results are normalized (Table 3 and Figure 5).



**Figure 5.** The normalized S value of each factor in the study area.

**Table 3.** The 12 susceptibility indexes of the loess landslide in the study area

Factors	$S_{CF}$	Normalized $S_{CF}$	$S_W$	Normalized $S_W$	$S_I$	Normalized $S_I$
Altitude	1.688155641	1.43	5.150495705	1.26	4.697856841	1.44
Slope	1.41891446	0.92	3.336565972	1.06	3.042007717	0.93
Aspect	0.898600963	0.41	1.465036763	0.67	1.416765423	0.43
Curvature	1.196644714	0.79	2.855810308	0.89	2.685647148	0.82
Plan curvature	1.158014129	0.83	3.0020889	0.87	2.805750813	0.86
Profile curvature	1.09886579	0.67	2.435052377	0.82	2.247890036	0.69
Roughness	1.340586274	1.08	3.895171347	1.00	3.088135409	0.95
Relief amplitude	1.478893993	1.31	4.722414083	1.11	4.413450141	1.35
Stratum lithology	1.670676325	2.10	7.580035321	1.25	6.8816904	2.11
Distance to faults	1.081167547	0.52	1.860457967	0.81	1.755280914	0.54
Distance to roads	1.40670078	0.92	3.313498213	1.05	2.479135575	0.76
Distance to rivers	1.622626683	1.03	3.721115156	1.21	3.644729969	1.12

Among the 12 factors, lithology, altitude, and relief amplitude are the key control factors of landslide development. The distance to rivers, roughness, slope, and distance to roads are moderate sensitive to landslide. The slope aspect, curvature and distance to faults have relatively weak control effect on landslide.

## 6. Conclusion

(1) According to the Certainty Factor (CF) method, the Weights-of-evidence method (WOE) method and the amount of information (I) analysis of the loess landslide in Tianshui City area, the most favorable factors for the occurrence of landslide in the 12 factors are as follows: altitude between: 1200m to 1400 m, slope between  $10^\circ$  to  $15^\circ$ , aspect of southwest, curvature between -0.5 to 0.5, plan curvature between -0.5 to 0.5, profile curvature between -0.5 to 0.5, roughness between 1 to 1.05, relief amplitude between 60 m to 120 m, stratum lithology of the Quaternary Upper Pleistocene ( $Q_3$ ) Malan loess and the Neogene (N) mudstone distribution areas, distance to faults between 4000m to 5000m, distance to rivers between 1200m to 1600m, distance to roads between 500m to 1500m. The above 12 factors are the susceptible factors of loess landslide hazard. Their responses and susceptibility to landslide is the highest, which makes them the key factors of landslide development.

(2) Among the 12 causative factors, the three factors of lithology, altitude and relief amplitude are the key factors controlling the landslide development according to the susceptibility index analysis. The susceptibility of buffer zone of rivers/roads, roughness, and slope to the development of landslide is moderate. Aspect, curvature, and fault buffer have relatively weak control effects on landslide.

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