Susceptibility Assessment of Single Gully Debris Flow Based on AHP and Extension Method

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Abstract

Debris flow mainly happens in mountainous areas all around the world with deadly social and economic impacts. With the speedy development of the mountainous economy, the debris flow susceptibility evaluation in the mountainous areas is of crucial importance for the safety of mountainous life and economy. Yunnan province of China is one of the worst hitting areas by debris flow in the world. In this paper, debris flow susceptibility assessment of Datong and Taicun gully near the first bend of Jinsha River has been done with the help of site investigation and GIS and remote sensing techniques. Eight causative factors, including slope, topographic wetness index, sediments transport index, ground roughness, basin area, bending coefficient, source material, and normalised difference vegetation index, have been selected for debris flow susceptibility evaluation. Analytical hierarchy process combined with Extension method has been used to calculate the susceptibility level of Datong and Taicun gullies. The evaluation result shows that both the gullies have a moderate susceptibility to debris flow. The result suggests that all the ongoing engineering projects such as mining and road construction work should be done with all precautionary measures, and the excavated material should adequately store in the gullies.

Keywords: Geological Disaster; Debris Flow Susceptibility; GIS and Remote Sensing; AHP; Extension Method.

1. Introduction

Debris flow is a two-phase fluid composed of soil, rock or organic matter flowing downslope under the influence of gravity. Debris flow can be very rapid and it may happen without any warning, because of this nature debris flow is one of the most hazardous geological disaster. Debris flow usually happens in mountainous areas. With the rapid development of the mountain economy, the demand for soil resources increasing, due to the lack of resource disorders, the circulation zones and accumulated areas generated by debris flow activity is generally comparatively flat, frequently becoming an important place for mountain villages and towns to build, mountain rail, highways, and other transport hubs often choose the large and medium debris flow accumulated areas. The world's population is estimated to live nearly 10 percent in mountainous areas [1]. Natural disasters in mountainous areas, represented by landslide and debris flow, pose a great threat to human life and property [2-5]. The debris flow is a devastating geomorphological event due to high velocity (up to 56 km per hour) and good erosion quality besides the statistics; it can be combined

with large boulders and other rock remains [6]. Debris flow can move the object as big as a building or fill up structures with the fast accumulated deposits and organic material [7, 8].

In recent decades the study of the susceptibility to debris flow is rapidly improving with the latest growth of 3S and computer technology [9]. The GIS techniques make the debris flow susceptibility comparatively relaxed and these tools are very useful in data assessment. In general, the different approaches used in determining susceptibility to debris flow can be divided into qualitative and quantitative methods [10]. In the literature, many researchers worldwide worked on the susceptibility assessment of debris flow and applied different research methodologies, including artificial neural network [11], analytic hierarchy process [12-14], frequency ratio (FR) [15, 16], weights of evidence [17], certainty factor [18], factor analysis method [19], logistic regression [20, 21], gradient boosting machine [22], bivariate and multivariate statistical analyses [23], Fuzzy c-means clustering [24, 25], index of entropy [26], Extension method [13] and information value method [27].

Despite significant scientific advancements in debris flow assessment, only a few studies are available on the susceptibility assessment of a single-gully debris flow in the literature. In consideration of the shortcomings of previous studies, the foremost goal of this article is to study the susceptibility assessment of a single-gully debris flow. The debris flow susceptibility assessment of Datong and Taicun gully, sharing their accumulated fan, has been considered a research object in this study. This assessment can help prevent the consequences of future events and understand the importance of the main factors that cause debris flows. Eight evaluating factors including, slope, Topographic Wetness Index (TWI), Sediments Transport Index (STI), ground roughness, basin area, bending coefficient, source material and Normalised Difference Vegetation Index (NDVI) were selected for debris flow susceptibility assessment on the basis of field investigation, 3S technology and previous research practices.

To conclude how key variables influence debris flow susceptibility, the numerical weights of the individual factors according to their influencing power in debris flow susceptibility has been determined with Analytical hierarchy process (AHP). The AHP method has been widely used in hazard evaluation [12, 28-30]. One of the most powerful characteristics of the AHP method is its potential to determine quantitative and qualitative criteria and alternatives on the same scale of preferences [31]. In addition, weights and major variables have been combined with the Extension method to evaluate debris flow susceptibility level of the debris flow gullies.

The key objectives of this study are; to establish key parameters of single-gully debris flow using field investigation and 3S technologies, to quantify the impact of key parameters on debris flow susceptibility, and propose a combined model that explains debris flow susceptibility level. The AHP method, when combined with Extension theory, was found to determine the susceptibility of single-gully debris flow successfully. The statistical ability and accuracy of the findings were found to be accurate by comparing with the previous studies and the ground conditions of debris flow gullies. The findings acquired in this research have practical consequences for the implementation of potential debris-flow disaster prevention and hazard reduction measures in similar single gully debris flow catchments.

2. Study Area

The research area is located near the first bend of the Jinsha River, which is connected to Shigu Town, Yunnan Province, China. Datong and Taicun gully located on the right bank of the Jinsha River at a distance of 4.4 km towards the north from the first bend of the Jinsha River. The study area is positioned in the area of intense collision, extrusion, and compression between the Indian and Eurasian plate, forming the contraction and sliding of different block tectonic units. Under the comprehensive action of the endogenic and exogenic geological process, the present deep valley and high mountain alternate arrangement are finally formed. The geographical location of the study area is shown in Figure 1.

The elevation difference in the study area is generally above a kilometer; the lowest elevation is along the Jinsha River, with an altitude of 1850 m±. The highest elevation is 5596 m near the Yulong Snow Mountain, and the elevation of the debris flow catchments is mainly 1800~3200 m (Figure 1).

2.1. Topography

According to the geographical zone of China, the study area belongs to the southwestern Tibetan Plateau geomorphic region. Further detailed division, it belongs to the freezing denudation and erosion cutting plateau area in western Sichuan-southern Tibet to the freezing denudation and erosion cutting sub-region in southern Qinghai-western Sichuan. Divided by genetic type, the study area is dominated by erosion, denudation, and ice erosion. Divided by morphological characteristics, the first bend of the Jinsha River is a typical alpine canyon area. The river is deeply formed a "V"-shaped canyon. The average width of the river is usually 80~150 m. However, the research area belongs to the wide valley section, with the river width of about 300~500 m.

The study area has typical alpine valley geomorphology. The slope angle of Datong and Taicun main gullies is greater than 35° with some up to 50-65° and more (Figure 2). The topographic features of the Datong and Taicun gully are shown in Table 1.

Table 1. Topographic features of Datong d Taicun Gully

Parameters	Datong gully	Taicun gully
Basin area /km	4.39	4.63
The linear length of the main gully /km	2.69	2.25
Main gully bending coefficient	1.02	1.03
The maximum relative elevation difference /km	1.144	1.339
The main gully curve length /km	2.76	2.31
The average ratio of the main gully /%	22.75	22.53
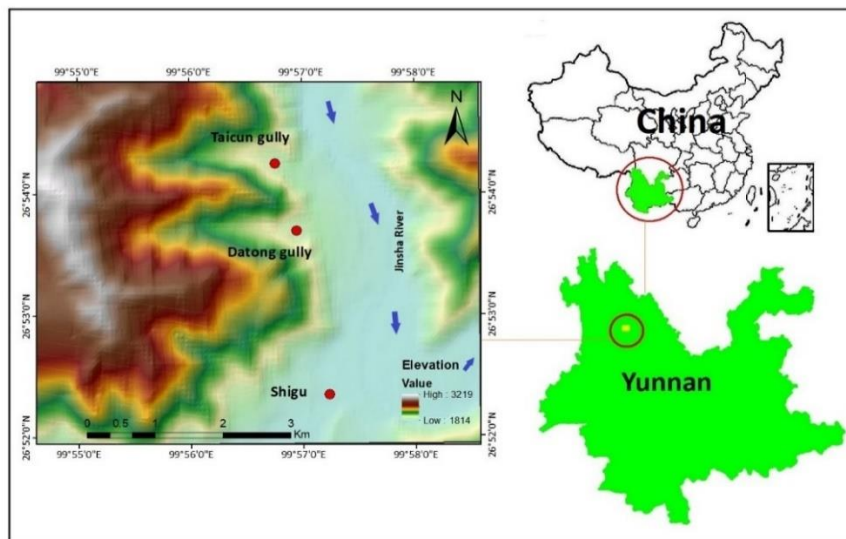
Figure 1. Geographical location of the study area
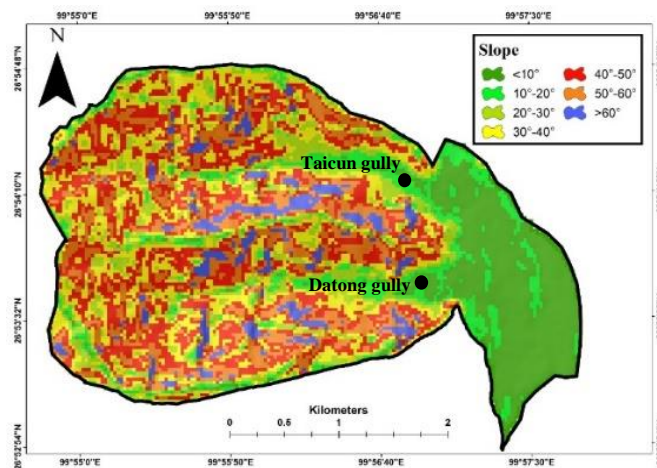
Figure 2. Slope map of Datong and Taicun gully

2.2. Climate

The monsoon climate characteristics in the Jinsha River basin are characterized based on the dry and wet seasons affected by the southwest and southeast monsoon. The precipitation is concentrated on the rainy season in the watershed, so the heavy rains in the watershed mainly occurred from June to August. The average annual and monthly rainfall of the study area is 834.3 and 69.7 mm, 24 h maximum rainfall was 106 mm, and the average number of precipitation a year is 138 days. The average temperature of the study area is 10.74℃, the extreme maximum and minimum temperature is 32.3 and -10.3℃ (Figure 3). The average wind speed of 4.83 m/s, with a maximum wind speed of 18.3m/s, the maximum wind direction is W.
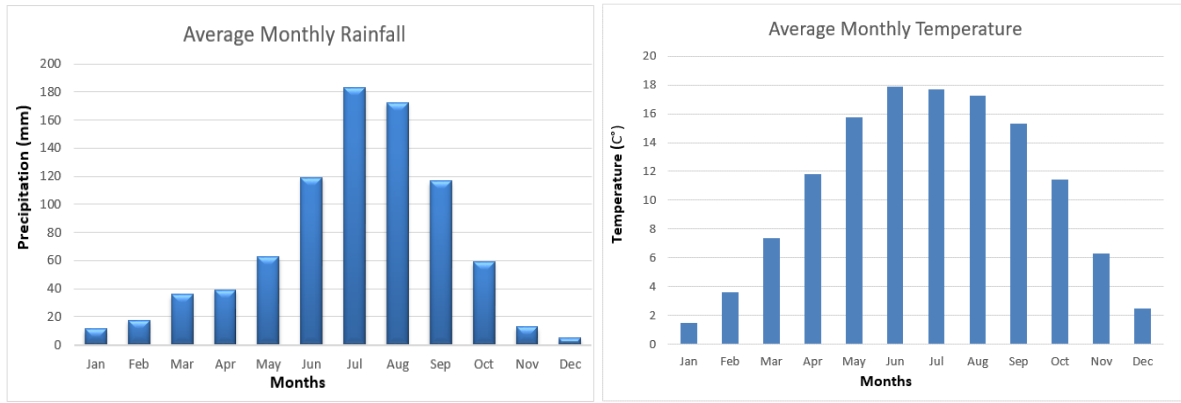
Figure 3. Average monthly precipitation (left), average monthly temperature (right). (1990-2019)

2.3. Geological and Engineering Geological Settings

The exposed geological strata of Datong and Taicun catchments consist of Quaternary colluvium deposits (Q_k), Crystalline Limestone and marbles (C_1), and Dolomite or limestone (D_1h). The main exposed strata in the study area are Cambrian, Devonian, and Triassic; the geological map of the study area is shown in Figure 4. Since the Paleozoic, the study area has undergone multi-stage movement and transformation, forming more complex folds and faults with different properties. Due to the strong extrusion of the Indian plate into the Eurasian plate, large-scale superimposition, dislocation, and slip occurred among the blocks divided by the fault zones, resulting in large-scale thrust nappe and translational shear or strike-slip in the region. The study area belongs to east mountain fault zone of the Jinsha River, and the geological structural activity is relatively strong. The Daju-Lijiang fault and Longpan-Qiaohou fault are active that highly impact the study area. According to the relevant seismic data several earthquakes of magnitude ≥4.7 has been recorded in the study area as shown in the Figure 5(a). The seismic activity in the study area is strong and the seismic intensity reaches level IX (Figure 5(b)).
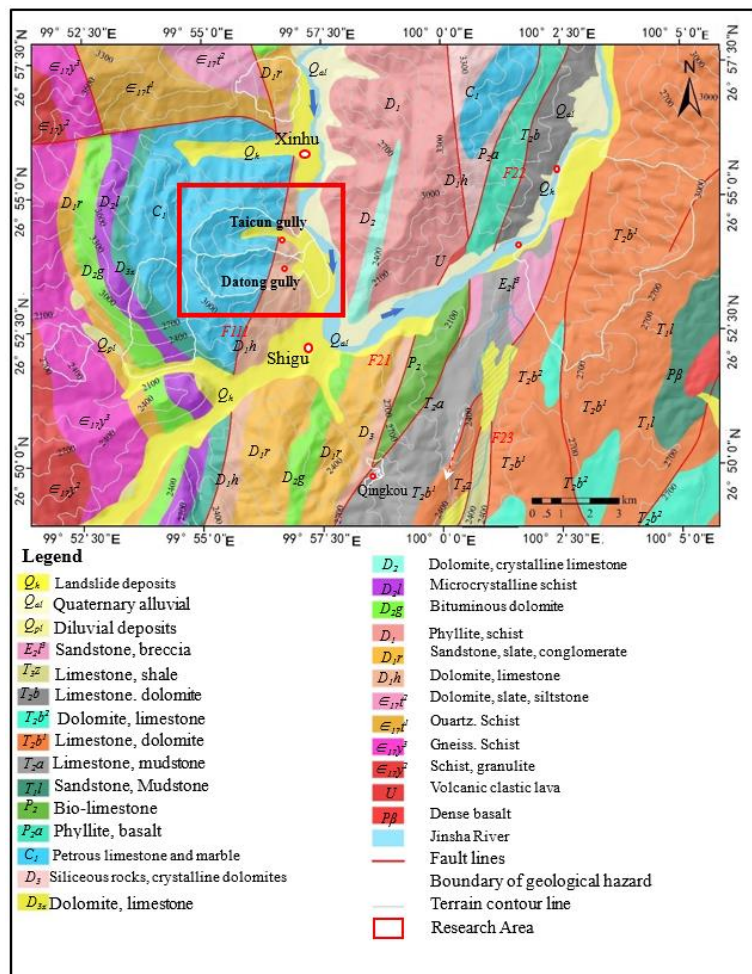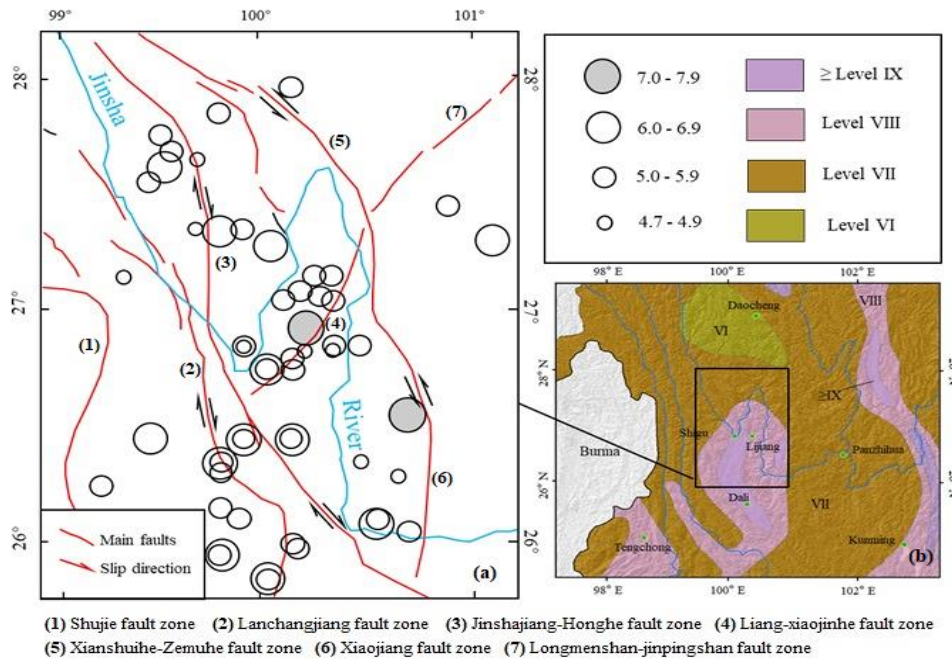

Figure 4. Geological map of the study area

Figure 5. The study area structural features, (a) The distribution of faults and earthquakes, (b) earthquake intensity divisions

The volume of loose material is an essential parameter for the debris flow initiation. The distributed loose source material was calculated during the field investigation. The distributed landslide collapse, rock avalanche, debris flow deposits, and unstable slopes were found in the study area. The accumulated loose source material varies from a minimum of 1mm to a maximum of 1 m in size. Due to the intrusion of limestone in the watershed, stone quarries existing in both the debris flow gullies; producing large amounts of loose material (Figures 8 and 12). Distributed loose course material and medium to large size crystalline limestone and marble boulders were found buried in loess in the accumulated fan. The viscosity of the debris flow residue material is normally determined by the nature of available material resources. Considering these, two parallel samples were collected from Datong gully accumulation fan during the field investigation for the sieve analysis test (Figure 6 (a, b)). The fine material of less than 1mm was taken back to the laboratory for laser particle analysis test. The analysis confirms that the Datong gully debris flow accumulation is mainly comprised of moderately textured soils, and the clay volume (<0.005 mm) is scarce (1.72%); consequently, the debris flow can be assumed to be low viscosity [32].

Based on the field investigation, the estimated source material statistics of Datong and Taicun gully are 151.53×10^4 and 15.98×10^4 m³. In which 2.18×10^4 m³ in Datong and 2.17×10^4 m³ in Taicun gully is unstable material and likely to be part of debris flow initiation. The characteristics of the Datong and Taicun watersheds are shown in Figures 7 to 13.

The groundwater also plays a major role in landslide and debris flow initiation. Groundwater flows in the pores and fractures of soil and rocks affect the mechanical and environmental boundary conditions such as weakening soil bond strength, reducing friction angles, and apply seepage forces [33, 34]. There are three types of groundwater present in the study area, i.e., underground pore water in loose deposits, bedrock fissure water in hillsides, and karst phenomena are developed to different degrees in these two gullies, so there is a small amount of karst water.

Figure 6. The particle size distribution of the two parallel sample in Datong gully (a) sample 1, (b) sample 2

Figure 7. Full view of Datong and Taicun gully from the accumulated fan
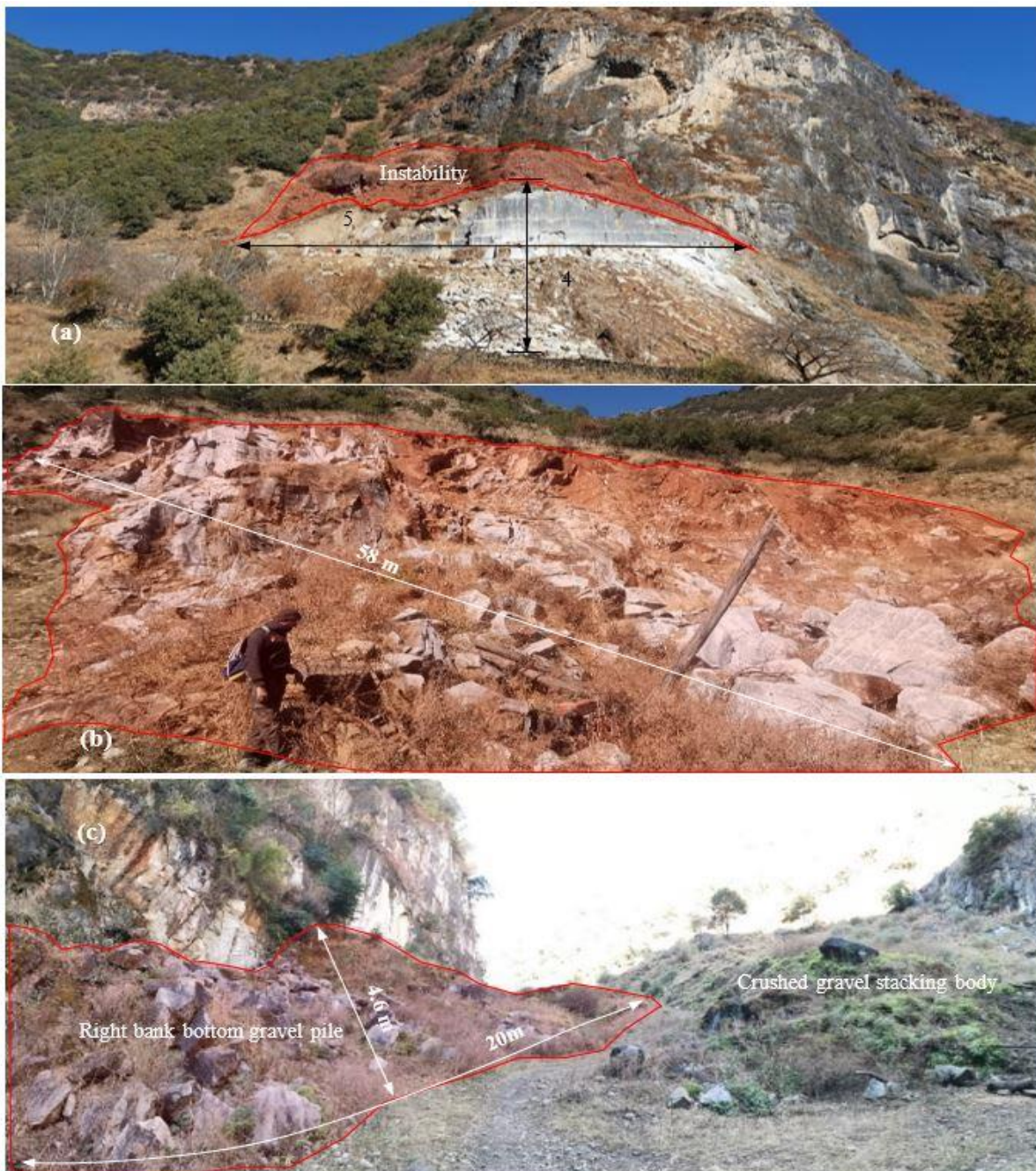
Figure 8. Datong gully (a) Stone quarry, (b) Crushed boulder deposits, (c) loose gravel and boulder deposits
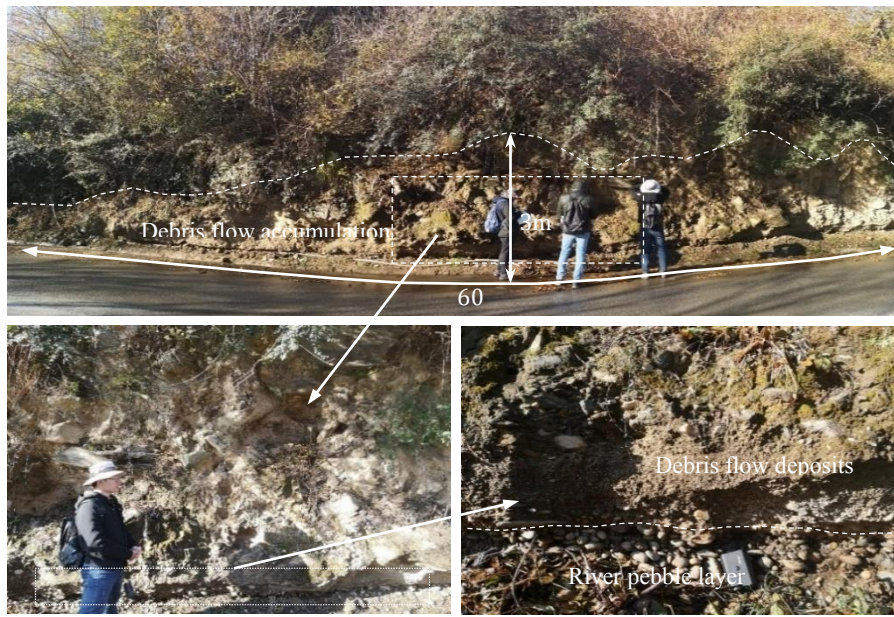
Figure 9. The boundary between the ancient debris flow and river facies

Figure 10. Taicun gully (a) caving area at main channel left side, (b) loose gravel and boulders at the bottom of the main channel

Figure 11. Overview of the artificially excavated slope profile for a house construction near highways
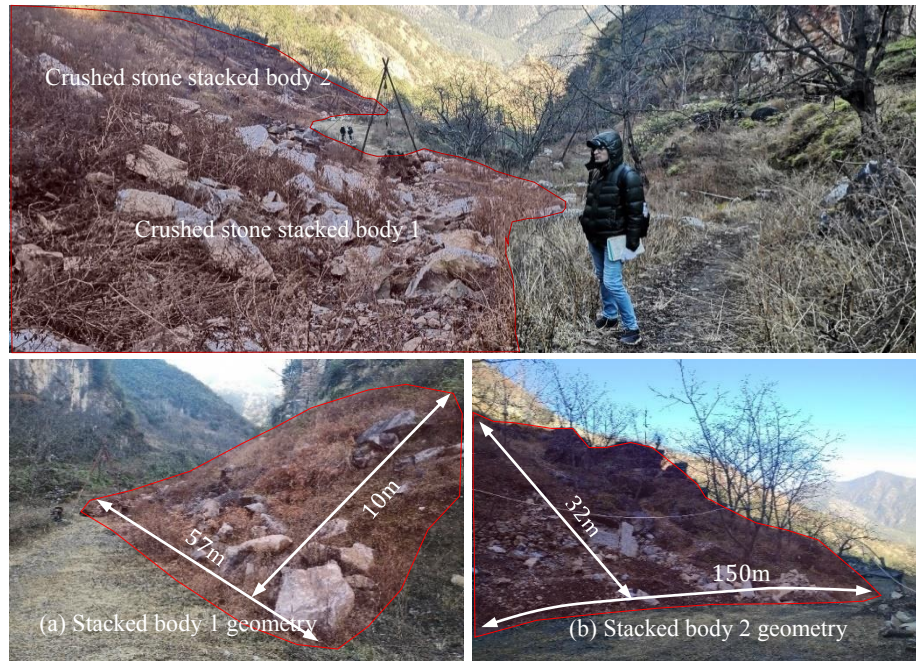
Figure 12. Overview and distribution geometry of crushed and artificially stacked material at the left bank of the Taicun gully main channel
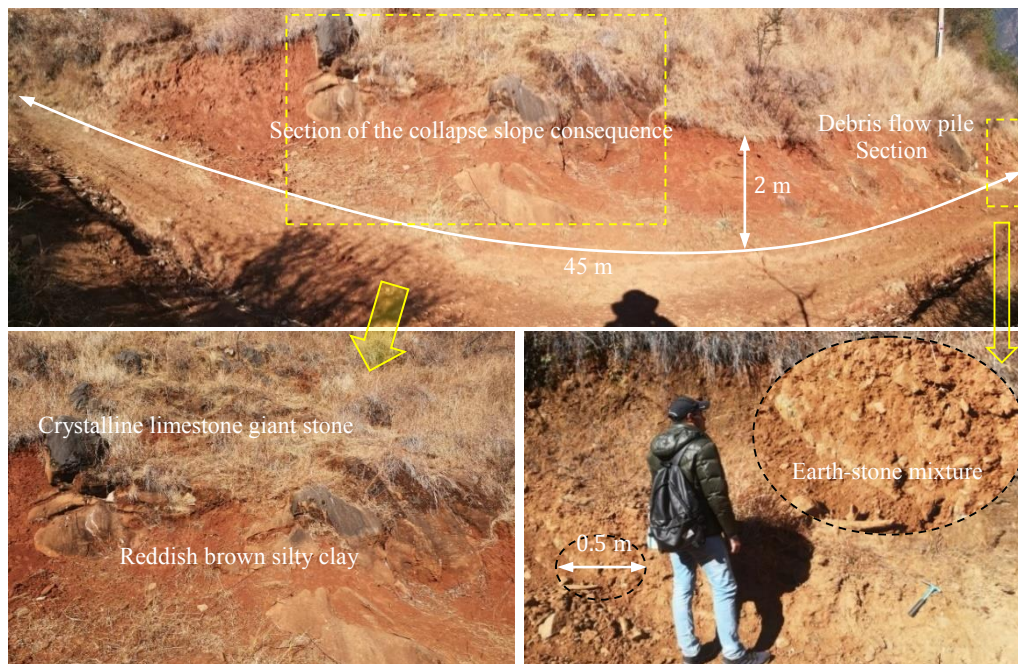
Figure 13. The outcrop slope at the left bank of the Taicun gully main channel is transformed into a mixed debris flow deposit by the disintegrated slope area containing rock

3. Material and Methods

3.1. Data Used

This study includes four main stages; (I) the first stage dealt with data acquisition and information about the study area. These data and information include geotechnical, geological, hydrogeological, topographical, and rainfall information. (II) The second stage dealt with selecting causative factors based on the field investigation and previous research experiences. (III) In the third stage, the weight and the influencing power of individual parameters in debris flow initiation have been calculated using the AHP method. (IV) Finally, the susceptibility level of Datong and Taicun gully was evaluated using the Extension method. The flowchart of the steps involved in the susceptibility evaluation of Datong and Taicun gully is given in Figure 14.
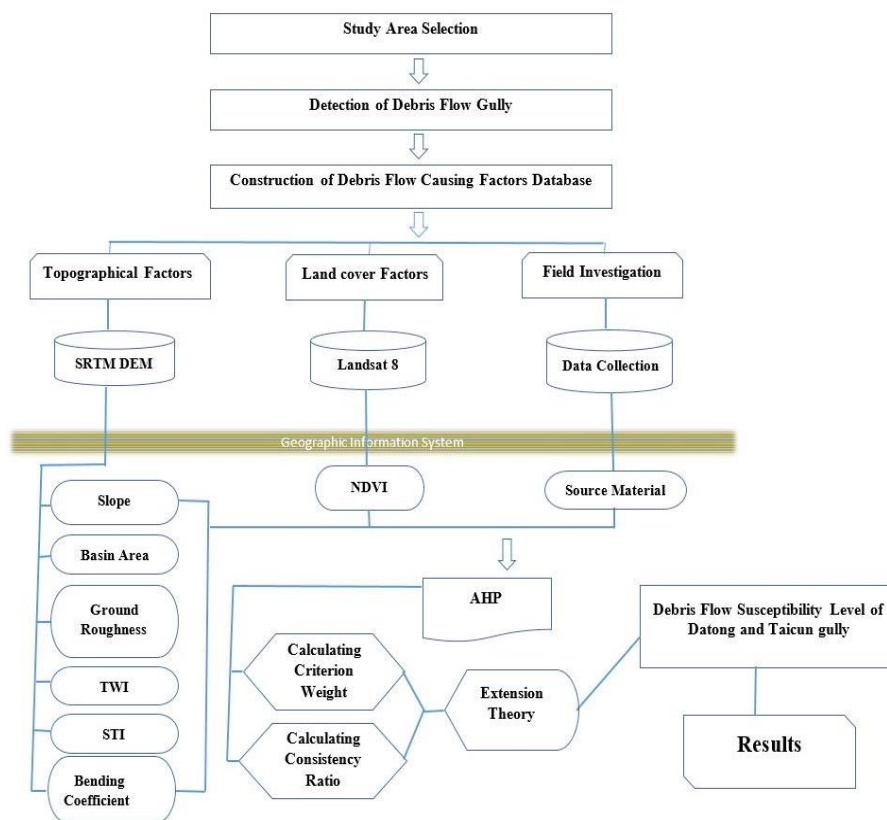
Figure 1. Flowchart of the research work

3.2. Model Selection

Several causative factors influence the susceptibility of debris flow. The Multi-Criteria Analysis (MCA) with the concept of weight has been used for debris flow susceptibility zonation of Datong and Taicun gully. MCA in the paper context is also referred to as MADA (Multi-Attribute Decision Analysis), wherein a number of causative factors are analysed to reach a common objective, i.e., debris flow susceptibility assessment. In the present studies, AHP combined with Extension theory has been used for the Datong and Taicun gully debris flow susceptibility assessment.

3.2.1. Analytical Hierarchy Process

One of the primary concerns in decision theory or multi-parameter evaluation is estimating the relative weight of each factor and its influence; in our case, debris flows susceptibility with respect to the other. This is a task that involves human judgment complemented by mathematical methods. As all conditional factors cannot be weighted equally for the susceptibility assessment, a weighted technique must be used where the relative value of the parameters defines the weightage.

There are a variety of approaches available to deal with such concerns. In the present study, we used Saaty's analytic hierarchy process [35], referred to as AHP, the most broadly approved scaling method. The weights of a variable establish a pair-wise judgemental matrix of variables whose entries signify the strength with which one component is dominant over another. AHP is a process based on decision theory in which it is necessary to compare each criterion from a set of choices or alternatives. It indicates the most accurate methodology for calculating the weight of criteria and estimating the relative magnitude of factors through pair-wise comparison with experts' judgment and experience. It directs the importance of a certain factor in debris flow assessment by co-relating with other elements through a statistical comparison. The scores given are based on reasonable prioritisation of the factor for inducing susceptibility of debris flow and depend on the estimation of the expert following the evaluation scale given by Saaty (2008) [36]. The grading of comparative factors is done by allotting weight ranges between 1 and 9, where 1 directs the same importance, and 9 represents the extreme importance of a particular factor over another, as shown in Table 2. The AHP calculations in this study were done in Microsoft Excel using the following steps [37]:

(i) Add the quantities in the pair-wise matrix's columns.

$$C_{ij} = \sum_{i=1}^{n} C_{ij} \tag{1}$$

(ii) To obtain a normalised pair-wise matrix, the matrix parameter was divided by the column's sum, respectively.

$$A_{ij} = \frac{C_{ij}}{\sum_{i=1}^{n} C_{ij}} \qquad (2)$$

(iii) To obtain each criteria weight, the summation of the matrix's normalised columns was divided by the amount of parameters applied.

$$W_{ij} = \frac{\sum_{j=1}^{n} A_{ij}}{n} \qquad (3)$$

Where n is the number of parameters and C_{ij} is the pair-wise matrix, A_{ij} is the normalised value and W_{ij} is the criteria weight.

Table 2. Pair-wise comparison 9-point rating scale in AHP, after [35]

Dominant values	Description	Explanation
1	Equal importance	Two factors contribute equally
3	Moderate importance	judgement slightly favour one factor over another
5	High prevalence	judgement highly favour one factor over another
7	Very high prevalence	Activity is very highly favoured over another
9	Extremely high prevalence	Activity is extremely favoured over another
2, 4, 6, 8	Intermediate values	used when comprises is needed

Though the comparisons in AHP are assigning by expert judgement, but still there could be inconsistency found in calculations. The consistency is derived in AHP by coherence ratio, which is given by Saaty (2008) [36] given in Table 3.

Table 3. Random index values

n	1	2	3	4	5	6	7	8	9	10
RI	0.0	0.0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

RI= random consistency index.

$$CR = \frac{CI}{RI} \qquad (4)$$

Where;

$$CI = \frac{\lambda_{max} - n}{n} \qquad (5)$$

Where λ_{max} is the Principal Eigen Value and can be determined as; $\lambda_{max} = \Sigma$ of the products between each variable of the priority vector multiplied by column totals. Whereas n is the total number causing parameters.

The consistency ratio will be calculated in order to find the continuity of the pair-wise compared weights [38]. The uniqueness of the AHP method is that it provides *CR* as a relationship between the degree of consistency and inconsistency. The suitable value of *CR* is 0.1 for all large matrices, i.e., *n*>5. Therefore, a *CR* of 0.1 or less is of reliable importance [39]; however, a *CR* above 0.1 needs to review the conclusions in the matrix.

3.2.2. Extension Theory

Cai (1983) proposed a new transverse discipline, Extenics [40]. Extenics is an interdisciplinary subject; the basic method is the Extension method. The extensibility of things, laws and methods can be studied by formalized models, which can ultimately solve the contradictions. A comprehensive evaluation of things using the knowledge of extension requires an effective combination of the quality and quantity of the evaluation object's characteristics.

The impacts of various causative variables on the susceptibility of debris flow can vary considerably. Influence deviation can be seen as an issue of contradiction and inconsistency. The method of extension is designed to solve this sort of difficulty by integrating the various degrees of influence of all causative variables in order to deduce an ultimate and complete susceptibility result [13].

Extension set and matter-element theory are the fundamental theories of the Extension method. The matter-element treats things as a ternary group *R*. The matter-element can be represented by Equation 6:

$$R = (N, C, V) \qquad (6)$$

In which the basic element (debris flow gully) can be represented by N, the basic element's characteristics (Causative factors) can be represented by C, and the value of the characteristics (for susceptibility analysis) can be represented by V respectively.

In the classical fuzzy set, the value range is [0, 1], in which 0 denotes that things have certain characteristics, 1 denotes that things do not have certain properties. In simple words, 0 and 1 denote whether things have certain characteristics or not, respectively. Compare to the classic fuzzy set [0, 1]; Extension sets are represented by real numbers [-∞, +∞]; which means that the extension theory not only study whether a component belongs to a set but also defines the grade of its belonging [41, 42].

Let U be the environment of an item and x be a component of U, the extension set of X on U is described as the set of ordered pairs as shown in Equation 7:

$$X = \left\{ \frac{x,y}{x} \in U, y = k(x) \in (-\infty, +\infty) \right\}$$

(7)

In which $k(x)$ is the correlation function of the X extension set, which is used to describe the connection between the x variable and the X extension set. The consequence of $k(x)$ may be positive, negative, or zero. When $k(x) > 0$, X is referred to as a positive class, simply mean belongs to the set and defines the grade of its belonging to the set. When $k(x) < 0$, X is considered a negative class simply means that it does not relate to the set, it defines the grade to which the parameter does not belong to the set. When $k(x) = 0$, X is considered a boundary zero [43].

3.2.2.1. Extension Evaluation Steps

(a) Determining Extension set:

$$R_{0J} = (N_j, C, V_j) = \begin{bmatrix} N_j, & C_1, V_{1j} \\ & C_2, V_{2j} \\ & \ldots, \ldots \\ & C_n, V_{nj} \end{bmatrix} = \begin{bmatrix} N_j, & C_1, (a_{1j}, b_{1j}) \\ & C_2, (a_{2j}, b_{2j}) \\ & \ldots & \ldots \\ & C_n, (a_{nj}, b_{nj}) \end{bmatrix}$$

(8)

Where N_j represents the debris flow susceptibility level, C_i (i=1, 2, 3.....n) represents the parameters of debris flow susceptibility, V_{ij} represents the range of parameter's values, and the classical domain is the value of each parameter in different evaluation levels.

Nodal elements are ranges of values for each susceptibility level for each factor:

$$R_P = (P, C, V_P) = \begin{bmatrix} P, & C_1, & V_{1P} \\ & C_2, & V_{2P} \\ & \ldots, \ldots \\ & C_n, & V_{nP} \end{bmatrix} = \begin{bmatrix} P, & C_1, & (a_{1P}, b_{1P}) \\ C_2, & & (a_{2P}, b_{2P}) \\ \ldots & & \ldots \\ C_n, & & (a_{nP}, b_{nP}) \end{bmatrix}$$

(9)

Where P denotes debris flow gully in our case, that is, the whole level of debris flow susceptibility, and V_{ip} denotes the range of values of P with respect to the factor C_i, that is, the influencing factor of P.

(b) Determining the Matter-element:

$$R = (P, C, v) \begin{bmatrix} P, & C_1, v_1 \\ & C_2, v_2 \\ & \ldots, \ldots \\ & C_n, v_n \end{bmatrix}$$

(10)

Where, P is the debris flow gully to be assessed, C_i is the factor influencing the susceptibility level, and v_i represents P's level of C_i, which is the data collected from the thing to be evaluated.

(c) Determining the value of the correlation function

The correlation degree of each individual evaluation index is:

$$K_t(v_i) = \begin{cases} \dfrac{-\rho(v_i, V_{ij})}{|V_{ij}|} & v_i \in V_{ij} \\[4mm] \dfrac{\rho(v_i, V_{ij})}{\rho(v_i, V_{Pi}) - \rho(v_i, V_{ij})} & v_i \notin V_{ij} \end{cases} \tag{11}$$

Where;

$$\rho(v_i, V_{ij}) = \left| v_i - \frac{a_{ij} + b_{ij}}{2} \right| - \frac{b_{ij} - a_{ij}}{2}, \qquad |V_{ij}| = |b_{ij} - a_{ij}| \tag{12}$$

$$\rho(v_i, V_{Pi}) = \left| v_i - \frac{a_{Pi} + b_{Pi}}{2} \right| - \frac{b_{Pi} - a_{Pi}}{2} \tag{13}$$

4. Debris Flow Susceptibility Assessment

4.1. Assessment Factors

The selection of causative variables is a requirement for pre-processing in debris flow susceptibility assessment. Recent advances in GIS software and increased computational ability make it conceivable to use a considerably large amount of independent variables in data-driven debris flow susceptibility assessment. Debris flows are induced by various external ecological and internal geological variables [44]. Normally, debris flow formation involves three constraints: loose source material, topography, and rainfall [12]. The loose source material is the physical source of debris flow events and is linked to section lithology and geological structures by influencing the conflux mechanism [45]. Table 4 referenced the excessively used causative factors by various researchers for debris flow susceptibility assessment.

Precipitation is an important parameter that impacts debris flow susceptibility. However, in the current study, two debris flow gullies have been studied located in the same area receive the same amount of precipitation; therefore, precipitation is not considered as a debris flow causative parameter. The geographical distribution of soil moisture and sub-surface water pressure is influenced by topography, which is a major element in the spatial variability of hydrological environments [46, 47]. Because debris flows contain large quantities of water, the hydrological-topographic variable of soil moisture has been regarded as an essential parameter for debris flow evaluation in this study. Amongst several variables of the hydrological factors, topographic wetness index [48], sediments transport index [49], and ground roughness [50] have been selected in this work to examine the impact of these variables on debris flow susceptibility. The STI specifies the soil erosion, TWI assess soil moisture spatial distribution and ground roughness directly influence the ability of ground confluence and seepage. Hence TWI, STI, and ground roughness were taken into consideration in this article.

The average elevation of the Tibetan plateau is about 4500m; the Shigu area belongs to the low elevated area of the Tibetan plateau; therefore, the elevation is not considered in this study.

The amount of source material volume represents lithological properties and fault distribution to some degree; therefore, lithology and fault distribution were not considered. The basin area and bending coefficient of the main channel also represent the amount of flood intensity and its effect on the lithological composition of the debris flow catchment. Therefore basin area and bending coefficient are also taken as causative factors in this study.

As previously stated, causative factors can be used as driving factors in forecasting potential outbreaks of debris flows in studied areas [51]; however, there is no specific principle for choosing these factors exist [52]. In the present study, the causative parameters were chosen amongst those widely reported in the literature for debris flow susceptibility assessment. Field investigation and spatial analysis were carried out to determine the influence of each of these variables on the debris flow distribution in our study area. The correlation between debris flow distribution and different indicators proposed a causal influence. The eight most relevant influencing factors were preferred in this study, including slope (F1), TWI (F2), STI (F3), ground roughness (F4), basin area (F5), bending coefficient of the main channel (F6), source material (F7), and NDVI (F8) were selected as evaluation indicators in this study. These variables directly or indirectly impact the happening of debris flows and have been widely used in the assessment of debris flow susceptibility [45, 53].

F1 represents the debris flow gully slope angle. The slope angle was generated from the study area DEM with the help of ArcGIS software. Slope stability have direct physical relationship with the debris flow initiation and the phenomenology of landslides; greater angle indicated greater slope instability, and vice versa. The slope of the debris flow has a response angle of 20°- 30°, the maximum angle at which the loose material is stable [61]

Table 4. Assessment variables frequently used by researchers in debris flow susceptibility assessment

Factors	[54]	[55]	[56]	[12]	[57]	[58]	[23]	[19]	[45]	[59]	[60]
Slope	√	√	√	√	√	√	√	√	√	√	√
Elevation	√	√	√	√	√	√	√		√		√
Source material		√			√			√			√
Aspect	√		√						√	√	
TWI			√			√	√				
STI			√			√	√				
DTF								√	√	√	
Lithology				√				√	√		√
Ground roughness	√		√	√					√		
Vegetation cover		√					√	√	√	√	√
Basin area		√			√			√		√	√
Curvature of main channel					√	√	√	√		√	√
Main channel length					√			√			√
Rainfall intensity	√	√							√	√	

F2 represents TWI value of the debris flow gullies. Beven and Kirkby first proposed the topographic wetness index [48]. Many researchers in the literature used the TWI is a causative factor for landslide and debris flow susceptibility assessment [58, 62, 63]. The areas of high TWI values provide more favourable conditions for landslide and debris flow initiation [62]. The TWI values of the Datong and Taicun gully was determined from DEM by means of the spatial analysis tool in ArcGIS 10.3 using Equation 14;

$$TWI = ln(F_{ac} + 0.001)|((\% \ slope/100) + 0.001) \tag{14}$$

Where F_{ac} is Flow accumulation which could be acquired from DEM file.

F3 represents STI value of the debris flow catchments. Sediments transport index which originates from the Universal Soil Loss Equation (USLE) [64] is the measure of soil erosion and carrying in the flow channel [65]. It is the volume of material transport ability of a flow along the water channel. The larger the slope length, the higher the soil erosion because of the water deposition at the bottom. The STI values were prepared from the DEM file with the help of ArcGIS 10.3 spatial analysis tool using Equation 15;

$$STI = power\left(\frac{F_{ac}}{22.13, 0.6}\right) \times power\left(\frac{sin\left(Atan\left(\frac{slope(\%)}{100}\right)\right)}{0.0896, 1.3}\right) \tag{15}$$

Where F_{ac} is flow accumulation.

F4 represents ground roughness; ground roughness also influences debris flows and is perceived to be a significant evaluation factor. The ground roughness indicates the surface area ratio to the projective area for a given area [12]. It directly influences the ability of ground confluence and seepage. Ground roughness of the study area was evaluated from DEM using spatial analysis tool in ArcGIS.

F5 represents the basin area of the debris flow gullies. Basin area has a direct impact on the quantity of the loose source material. In general, a broader basin area would lead to a greater amount source material [25]. The extent of the debris flows is determined by source material volume. As a consequence, basin area is considered a major influence factor in the debris flow susceptibility evaluation. It was obtained through ArcGIS and google earth.

F6 denotes bending coefficient of the debris flow gully main channel. Bending coefficient is the proportion of the main channel's curve length to conventional length. This proportion represents the debris flow discharge environment. Currents may strike and erode the exposed lithology of the curvy channel. The hillsides stability will be reduced, and enhance the amount source materials in the main channel [66]. A debris flow catchment with a small amount of loose material is often distinguished by an outward and straight channel; because the stacked source material will be washed with the established debris flow in the main channel [13].

F7 is the available source materials in debris flow catchments. Sufficient loose source material in the debris flow gullies are the primary conditions for the formation of debris flow. Once the debris flow source is activated, it will

pose the first impact to the loose material distributed in the formation and circulation areas of the debris flow gully. The investigation of solid source material accumulated in the debris flow gullies has a crucial impact on debris flow initiation. The source material data was collected and evaluated from the field investigation.

F8 denotes NDVI values of the debris flow gullies. The NDVI value describes the vegetation cover of the study area. The literature shows that most debris flows occur in areas with less vegetation cover and NDVI values, especially less than 0. The NDVI values varied from −1 to 1; the higher the NDVI score, the heavier the vegetation cover [11]. The high NDVI value decreases the runoff erosion of the gully and reduces the chance and potential of debris flow. The area without vegetation cover has rapid and favourable convection to landslide and debris flow. The NDVI value of the research area was evaluated from Landsat-8 imaginary using ArcGIS Raster calculator.

4.2. Modelling Approach

Selecting the causing factors has highlighted a number of key parameters that are potentially important in the derivation of susceptibility assessment of debris flow. It is extremely necessary to combine them to drive a single representative value for susceptibility analysis; otherwise, they are independent variables which offer separate indication.

4.3. Assigning Weight

In this study, the AHP method was used to calculate the weight of one causative factor over another. One of the major benefits of using AHP is rearranging the complication of data set by the hierarchy with a pair-by-pair comparison between two variables, therefore minimising weighting inaccuracy while ensuring that different data processing is consistent. However, this method can vary from one expert to another, based on expert opinion, judgment, and ranking of the causative factor, which is, therefore, a minor drawback. Many researchers globally used the AHP method in their studies to assess debris flow susceptibility.

A pair-wise matrix was built, in which each criterion was correlated with other criteria, according to its importance, on a scale from 1 to 9, as can be seen in Table 4. As we have eight parameters, then we have eight by eight matrixes. The diagonal matrix elements are always 1, and one needs to complete up the upper triangular matrix. If the value of the decision is on the left side of 1, we shall set the numerical value of the decision. Suppose the value of the decision is on the right side of 1. In that case, we shall set the inverse value to build a debris flow susceptibility model and provide a method to determine the variable weights in the linear debris susceptibility model. The importance matrices for eight variables have been created in Microsoft Excel [37]. An importance matrix table has been obtained by adjusting the value for a pair of two variables, as shown in Table 5. These relationship scores have been achieved by field investigation and previous research experiences. The individual criteria weight was obtained following the steps explained in Section 3.2.1. above.

Table 5. Pair-wise comparison results of Debris flow causative factors

Judgement matrix	F1	F2	F3	F4	F5	F6	F7	F8
F1	1	2	3	4	6	7	6	6
F2	0.5	1	3	5	4	6	5	5
F3	0.333	0.333	1	3	4	5	6	6
F4	0.25	0.2	0.333	1	2	3	3	6
F5	0.167	0.25	0.25	0.5	1	5	4	3
F6	0.143	0.167	0.2	0.333	0.2	1	2	4
F7	0.167	0.2	0.167	0.333	0.25	0.5	1	2
F8	0.167	0.2	0.167	0.167	0.333	0.25	0.5	1
Σ (Sum)	2.727	4.35	8.117	14.33	17.78	27.75	27.5	33

Note: F1 = slope, F2= TWI, F3 = STI, F4 = ground roughness, F5 = basin area, F6 = bending coefficient, F7 = source material, F8 = NDVI

Let us look at how the pair-wise judgments were calculated with an understanding of F1 (slope). The significance matrix will be normalized and weighted using the "Eigen Vector" technique, as shown in Table 6.

Table 6. Normalized value determination

Comparison matrix	F1	F2	F3	F4	F5	F6	F7	F8
F1	1	2	3	4	6	7	6	6
Individual parameter column sum (as shown in Table 4)								
Σ (Sum)	2.727	4.35	8.117	14.33	17.78	27.75	27.5	33
Normalized weight (factor value/ Column sum)								
F1	1/2.727	2/4.35	3/8.117	4/14.33	6/17.78	7/27.75	6/27.5	6/33
Normalization	0.367	0.46	0.37	0.28	0.337	0.252	0.218	0.182

The weight of the parameter F1 in debris flow susceptibility was calculated using Equation 3:

Σ = 0.367+0.46+0.37+0.28+0.337+0.252+0.218+0.182/ 8 =0.31 (weight of F1 (slope)) or 31%.

The weight of other parameters were calculated in the same way. The individual weight of each causative factor finally obtained as: F1 (0.31) >F2 (0.25) >F3 (0.17) >F4 (0.091) >F5 (0.078) >F6 (0.042) >F7 (0.032) >F8 (0.025) respectively.

The final stage is to calculate the consistency ratio to measure how consistent the judgement is. The consistency ratio was calculated with Equation 4.

In our case by calculation the λ_{max} = 8.87, *CI* = 0.87, *RI* = 1.41 (Table 3 by Saaty (2008) [36]), *CR* = 0.08, which is less than 0.1; the ratio shows an acceptable degree of consistency in the pair-wise judgement, standing sufficient to distinguish the factor weights. The revision of the preferences matrix will be needed if the *CR* value is more than 0.1.

4.4. Susceptibility Assessment based on Extension Theory

Debris flow susceptibility are being calculated based on the causative variables and their weights. Four classes of susceptibility were established in this article: low, medium, high, very high. Since we have to analyse the susceptibility assessment of two debris flow gullies Datong and Taicun, in this paper, the matter-element was evaluated first for J=1 and 2, respectively. The eight causative factors, including slope, TWI, STI, ground roughness, basin area, bending coefficient, Source material and NDVI, are evaluated. The weight of each parameter calculated using the AHP method, as shown in Table 5.

The variable values are given in Table 7. As per previous literature, the matter-element ranges [VL, VU] of the four susceptibility degrees, i.e. low, moderate, high and very high for each variable, are determined. The neighbourhood domain range can be derived either from previous practical practice or calculated from the maximum and minimum values of each variable in the field survey [13]. The second one is being used in this study. The ranges and the neighbourhood domains are given in Table 8. The correlation function can be determined using Equation 11. From the value of the correlation function, the degree of correlation of the evaluated parameters with respect to the grade t is obtained according to the Equation 16:

$$K_t(P) = \sum_{i=1}^{n} W_i\, K_t(v_i) \tag{16}$$

Where W_i is the weight factor of each evaluation parameter, and $\sum W_i = 1$.

If $K_k(P) = \max K_t(P)$, then the susceptibility of debris flow is ranked *K*.

Table 7. Debris flow causative factors

Gully name	F1 (°)	F2	F3	F4	F5 (km²)	F6	F7 (× 10⁴ m³)	F8
Datong gully	45	12	200	1.5	4.39	1.02	2.18	0.159
Taicun gully	43	12	174	2	4.63	1.03	2.17	0.13

Note: F1 = slope, F2= TWI, F3 = STI, F4 = ground roughness, F5 = basin area, F6 = bending coefficient, F7 = source material, F8 = NDVI

Table 8. Matter-element variance of the susceptibility level

Susceptibility level and neighbourhood domain	F1(°)	F2	F3	F4	F5 (km2)	F6	F7 (× 10⁴ m³)	F8
Low	≤ 20	≤ 5	≤ 100	≤ 1.26	≤ 0.5 or ≥ 50	≤ 1.10	≤ 1	≥ 0.4
Moderate	20 - 30	5 - 10	100 – 200	1.26 – 1.46	0.5 - 10	1.10 – 1.25	1 – 10	0.24 – 0.4
High	30 - 40	10 - 15	200 – 300	1.46 – 2	10 – 30	1.25 – 1.40	10 – 100	0.16 – 0.24
Very High	≥ 40	≥ 15	≥ 300	≥ 2	≥ 30	≥ 1.40	≥ 100	≤ 0.16
neighborhood domain	0 - 70	0 - 25	0 - 500	0-3	0 - 40	0 - 2	0 - 200	-1 – 1

Note: F1 = slope, F2= TWI, F3 = STI, F4 = ground roughness, F5 = basin area, F6 = bending coefficient, F7 = source material, F8 = NDVI

The correlation degree of each grade of eight causative parameters of the susceptibility degree evaluation model is calculated by using the correlation function equation for Datong and Taicun debris flow catchments respectively, as shown in Table 9.

Table 9. Correlation degree of individual parameter of Datong and Taicun gullies on debris flow susceptibility

Level description	Low	Moderate	High	Very high
Datong gully				
F1	-0.157	-0.1178	-0.0523	0.1047
F2	-0.0917	-0.0356	0.0498	-0.1494
F3	-0.056	0	0	-0.168
F4	-0.01255	-0.0024	0.002493	-0.091
F5	-0.0366	0.6068	-0.0438	-0.3995
F6	0.0037	-0.0032	-0.1288	-0.0117
F7	-0.01124	0.0378	-0.02502	-0.0313
F8	-0.0056	-0.0022	-0.00003	0.00004
Taicun gully				
F1	-0.1444	-0.10205	-0.0314	0.0628
F2	-0.09174	-0.035571	0.0498	-0.1494
F3	-0.05013	0.029514	-0.02184	-0.21168
F4	-0.03870	-0.03191	0	0
F5	-0.03677	0.64428	-0.04189	-0.39577
F6	0.003267	-0.00283	-0.00777	-0.0518
F7	-0.01121	0.03744	-0.02506	-0.03131
F8	-0.005921	-0.00281	-0.00083	0.00129

Note: F1 = slope, F2= TWI, F3 = STI, F4 = ground roughness, F5 = basin area, F6 = bending coefficient, F7 = source material, F8 = NDVI

According to the combination weight coefficient and single correlation degree of eight evaluation factors, the comprehensive correlation degree of Datong and Taicun debris flow is calculated, as shown in Table 10. According to the evaluation results, the susceptibility level of Datong and Taicun debris flow is moderate. Datong and Taicun gullies are located at the same location, sharing their accumulation fan and because of the same environmental, topographic and geological environment, both catchments have similar debris flow susceptibility levels. The outcomes were compatible with the findings of the field investigation.

Table 10. Extension evaluation results of debris flow susceptibility of Datong and Taicun gully

Gully name	Low	Moderate	High	Very High	Susceptibility Level
Datong gully	-0.367	**0.483**	-0.198	-0.746	Moderate
Taicun gully	-0.376	**0.536**	-0.079	-0.776	Moderate

To check the validation of our study, the results were compared with the work done by Li et al. (2017) [25] (Debris flow susceptibility in the Wudongde dam area, Jinsha River) and Liang et al. (2020) [24] (susceptibility assessment of debris flow based on a semi-quantitative method). These studies were selected for comparison because of their similar topographical, meteorological, and geological environment to our case studied (Datong and Taicun gully).

Li et al. (2017) [25] used eight causative factors to evaluate the susceptibility assessment of 22 debris flow catchments along the Jinsha River close to Wudongde Dam site, Yunnan province of China. Out of 22 debris flow gullies, Xiabatian and Zhugongdi catchments were taken on the basis of basin area and other topographic features to compare with our case studied (Datong and Taicun gullies). Li et al. (2017) [25] used the rock engineering system and fuzzy C-means algorithm (RES_FCM) for debris flow susceptibility assessment. Based on the evaluated results Xiabatian have high and Zhugongdi catchment has moderate susceptibility to debris flow. Xiabatian catchment shows high susceptibility to debris flow because of the available large amount of source material and higher bending coefficient values than our case study, as shown in Table 11.

Liang et al. (2020) [24] studied the susceptibility assessment of 21 debris flow catchments in pinggu district, Beijing using FA, FCM, and ECM to classify and evaluate the susceptibility level of debris flow. Based on the basin area and other topographic features, out of 21 catchments, the evaluation results of Tawa and Hundong gullies were compared with the evaluation results of the Datong and Taicun gullies. The evaluation results of Liang et al. (2020) [24] shows that Tawa has high and Hundong catchment have moderate susceptibility to debris flow. The basin area and the ratio of available source material in Tawa gully are higher than those of Datong and Taicun gullies, making

their susceptibility level high. In contrast, the Hundong gully has a comparatively small basin area and less source material; that's why evaluation results show of moderate level.

From this comparison, it is worth noting that the basin area, bending coefficient, and the available amount of loose material in the debris flow catchments directly impact debris flow susceptibility level. The higher the amount of loose material higher will be the susceptibility level, even if the slope angle is than 30°. On the basis of the above comparison and field investigation analysis, we can conclude that the evaluation results of our study are satisfactory.

Table 11. Comparison of the current evaluation results to previous studies

Parameters	Li et al. (2017) [25]		Liang et al. (2020) [24]		Present study	
	Xiabatian gully	Zhugongdi gully	Tawa gully	Hundong gully	Datong gully	Taicun gully
Basin area (km^2)	3.1	6.5	6.65	5.31	4.39	4.63
Slope	36.1°	41.8°	23°	25°	45°	43°
Bending coefficient	1.19	1.15	1.08	1.03	1.02	1.03
Vegetation cover	0.45	0.4	0.52	0.62	0.15	0.13
Source material ($\times 10^4$ m^3)	904	316	18.457	6.443	2.18	2.17
Susceptibility level	High	Moderate	High	Moderate	Moderate	Moderate

5. Conclusions and Recommendations

The research area is located in the northwest of Yunnan province, which belongs to the upper streams of Jinsha River Tibetan Plateau. The research area is tectonically active and causes a large amount of landslide and debris flow every year. The Datong and Taicun gullies are located near the first bend of the Jinsha River, which has a very important geological significance. The study area belongs to the east mountain fault Zone of the Jinsha River and the geological structure-activity is relatively strong. The presence of active geological faults and mining activities in the debris flow gullies make it more susceptible to landsliding and debris flow. The active mining work is producing a large amount of solid source materials of various sizes. A large amount of separated large-sized collapsed boulders scattered in the debris flow catchments, which is difficult to be carried in normal rain, but once the heavy rain occurs, these solid source materials from mining work and collapsed deposits can be part of debris flow initiation.

A detailed field investigation was organized to collect data regarding the susceptibility assessment of debris flow in Datong and Taicun gully. The collected field data was analysed and interpreted with the help of GIS and Remote sensing techniques. Eight causative factors, including slope, TWI, STI, ground roughness, basin area, bending coefficient, source material, and NDVI, were considered to investigate and calculate the susceptibility assessment debris flow of Datong and Tai gully using AHP and Extension methods. The weightage of each causative factor was evaluated with pair-wise comparison using the AHP and priority given based on expert views. The individual influencing weight of each causative factors finally obtained as: slope (0.31)>TWI (0.25)>STI (0.168)>ground roughness (0.091)>basin area (0.078)>bending coefficient (0.042)>source material (0.032)>NDVI (0.025) respectively. The susceptibility assessment of Datong and Taicun gully was done using Extension Theory, which has a good competency to solve inconsistency and contradiction complications.

According to the combined weight coefficient and single correlation degree of eight evaluation factors, the comprehensive correlation degree of Datong and Taicun debris flow is calculated. Based on the evaluation results, the susceptibility level of Datong and Taicun debris flow gully is moderate.

Datong and Taicun gully located at the same location, sharing their accumulation fan and because of the same environmental, topographic and geological environment, both the gullies results in similar susceptibility level. The method used in this study is simple and convenient to implement. The AHP method, when combined with Extension theory, was found to determine the susceptibility of single-gully debris flow successfully. The statistical ability and accuracy of the findings were found to be satisfactory by comparing the evaluation results with previous studies and field investigation judgements.

However, there are some limitations to the approach used in this study: (1) the precipitation, which is a key factor in determining debris flow susceptibility, was not taken into account in this study. Susceptibility findings would be more reliable if precipitation variance for debris flow catchments is used. (2) The instruments utilized during fieldwork are too simple, and some key parameters, such as the amount of source material per square kilometre, are not precise enough. Divergences between site investigation findings and indoor interpretation consequences could be reduced further. (3) In the AHP method, the weight is assigned to the causal parameters based on expert opinion and judgments. The weight could be different from the actual values. The identification of precise weights also necessitates unrelenting efforts.

Based on the debris flow susceptibility analysis of the Datong and Taicun gully, the following recommendations are suggested:

- All the construction work, especially road construction, which is undergone in the study area, should be constructed with all the precautionary measures and properly store the excavated material;

- All the waste material produced from the mining work should be removed from the gully or compacted layer-wise not to be carried easily by fluid in rainy seasons;

- For all kinds of engineering projects and villagers, safety measures should be taken into account;

- For the awareness, local inhabitant investment in counteractive steps on the debris flow is highly demonstrated in public education and early warning systems.

6. Declarations

6.1. Author Contributions

Q.M. was responsible for writing and graphic production of the manuscript; J.C. supervised the field investigation; W.Q. was responsible for the manuscript's revision; J.Y. and N. were responsible for the calculations part; G.R. and M.A. were responsible for proofreading and references. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in article.

6.3. Funding

6.4. Acknowledgements

6.5. Conflicts of Interest

The authors declare no conflict of interest.

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