Landslides distribution at tributaries with different evolution stages in Jiangjia Gully, southwestern China

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Abstract: Landslide susceptibility assessment is of great significance for the disaster prediction and prevention. At present, most studies used statistical methods by the influence factors of landslide distribution, or based on physical models to determine the assessment result, the research of these methods was mainly focused on the gully scale. At the same time, these methods did not focus on the specific principle of material storage. In this paper, the surface erosion index, being the integral of the hypsometric curve, is adopted to explore the landslides distribution characteristic in different tributaries of the gully. Firstly, 81 tributaries of JJG are taken from DEM with 10 m grid cells, and the hypsometric curves are used to characterize their evolution stages; five stages are identified by the evolution index (EI, the integral of the hypsometric curves) and most tributaries are in relative youth stage with EI between 0.5 and 0.6. Then 906 landslides are interpreted from Quickbird satellite image of 0.61 m resolution. It is found that LD (LD = landslides number in a tributary/ the tributary area) increases exponentially with EI, while LA_p (LA_p = landslides area in a tributary/ the tributary area) fluctuates with EI, meaning that landslides are inclined to occur in tributaries with EI between 0.5 and 0.6, and thus these tributaries are the main material sources supplying for debris flows.

Key words: Hypsometric curve; Evolution stages; Tributaries; Landslides distribution

1 Introduction

Landslide susceptibility assessment over large areas is considered a preliminary step for the planning or design of the most appropriate risk mitigation measures. The use of statistics and physics based models is considered a useful tool for landslide susceptibility assessment (Amashi et al., 2019; Baena et al., 2019; Ciurleo et al., 2019; Hu et al., 2019; Rao et al., 2017; Singh et al., 2019; Xie et al., 2015). However, the research of these methods was mainly focused on the gully scale. At the same time, these methods did not focus on the specific principle of material storage, but carried out statistical or comprehensive analysis on the main factors affecting the landslides distribution.

Geomorphic evolution has been one of the important research topics in geomorphology, hypsometric analysis has been used to deal with erosional topography and the process of landform development (Bartolini et al., 2003; Li et al., 2011; Lv et al., 2005). Strahler (1952) asserted that different types of landform have different characteristic shape of their hypsometric curves, dividing landform into 'young' and 'mature' with the hypsometric integral decreasing. The integral can be used to indicate the geomorphological evolution state, in this meaning, it can be defined as the evolution index (EI) of a tributary (Kashani et al., 2019; Qureshi et al., 2019; Strahler, 1952, 1957). Meanwhile, the hypsometric curves are related to tributary form and erosional process, and are used to interpret landform development stages (Schumm, 1956; Strahler, 1952, 1957), which can represent the state of material storage of a tributary. In addition, the relationship between EI and tributary characteristics changes with scales. For example, the dissection index of tributaries presents various relationships to EI depending on scale of the tributaries. For the 5th-order tributaries, their correlation is r = 0.41, whereas for the 4th-order, it is r = 0.24, and it becomes negative correlation for the 3rd-order (Hamza et al., 2018). Combined with the results of field investigation, this study adopts the tributary scale that debris flow easily occurs to meet our research need.

For a given watershed, especially a small gully in mountains (below 100 km^2 and most below 10 km^2), the tributaries with different EI present various topographic characteristics. Similarly, significant difference exists in the distribution of landslides among various tributaries, landslides are frequent in some tributaries while occasional in others (Baum et al., 2005; Pradhan and Sameen, 2017; Wang et al., 2006; Wieczorek, 1996). Therefore, the relationship between EI and landslides distribution has special significance to reveal the landslides distribution in tributaries, which, however, has been gotten little attention in literatures.

In this paper, a case study is conducted in Jiangjia Gully (JJG), where weak and similar lithology, disparate topography, sparse vegetation, and unconsolidated deposits are widely distributed in tributaries. In addition, the debris flow behavior in JJG are representative, it is known for the high variety of debris flows; each debris-flow event consists of tens or hundreds surges of different flow regimes, velocities, discharges, and total volumes (Li et al., 2015; Li et al., 2013; Arai, 2017). In particular, the surges are composed of different materials, suggesting that they come from different sources (Xiang et al., 2015). In other words, each debris flow in JJG comes from different tributaries (Bollschweiler et al., 2007; Li et al., 2012; Li et al., 2013; Li et al., 2015). Generally, the flow surges are originated from different tributaries and the material supplies are mainly from landslides (including avalanches, soil failures and other slope processes) (Beguería, 2006). So the study of landslides distribution in different evolution stages is of great significance to reveal the landslides distribution characteristics of the tributaries, which can roughly determine the material supply and explain the formation mechanism of debris flow surges.

2 Study area and data collection

2.1 The setting of the study area

JJG is located in the Xiaojiang River of the Upper Changjiang River. The mainstream channel length is 1.39×10^4 m and the gully area is 4.84×10^7 m^2 (Fig. 1). This region undergoes active neotectonic movement, faults, and folds; and rocks are dominated by slate, dolomite, limestone, basalt and breccia rocks, which are easily weathered (Gabet and Mudd, 2006). The exposed strata in this gully is mainly shallow metamorphic rocks of the lower proterozoic Kunyang group, accounting for about 80% of the whole gully area (Wu et al., 1990). Generally, weak lithology, wide faults and sparse vegetation are the obvious characteristics of the gully, and the tributaries are in steep topography and intense landslide activity, with wide distribution of quaternary unconsolidated deposits. Loose materials are widely distributed in the gully and debris flows occur frequently, which are the major material sources for the debris flows. According to the statistics data, the landslides area reaches 16.4 km^2 that accounts for 39.7% of the gully area. As well, average annual sediment yield by debris flow is about 1.54×10^6 m^3 (Wu et al., 1990; Zhuang et al., 2015).

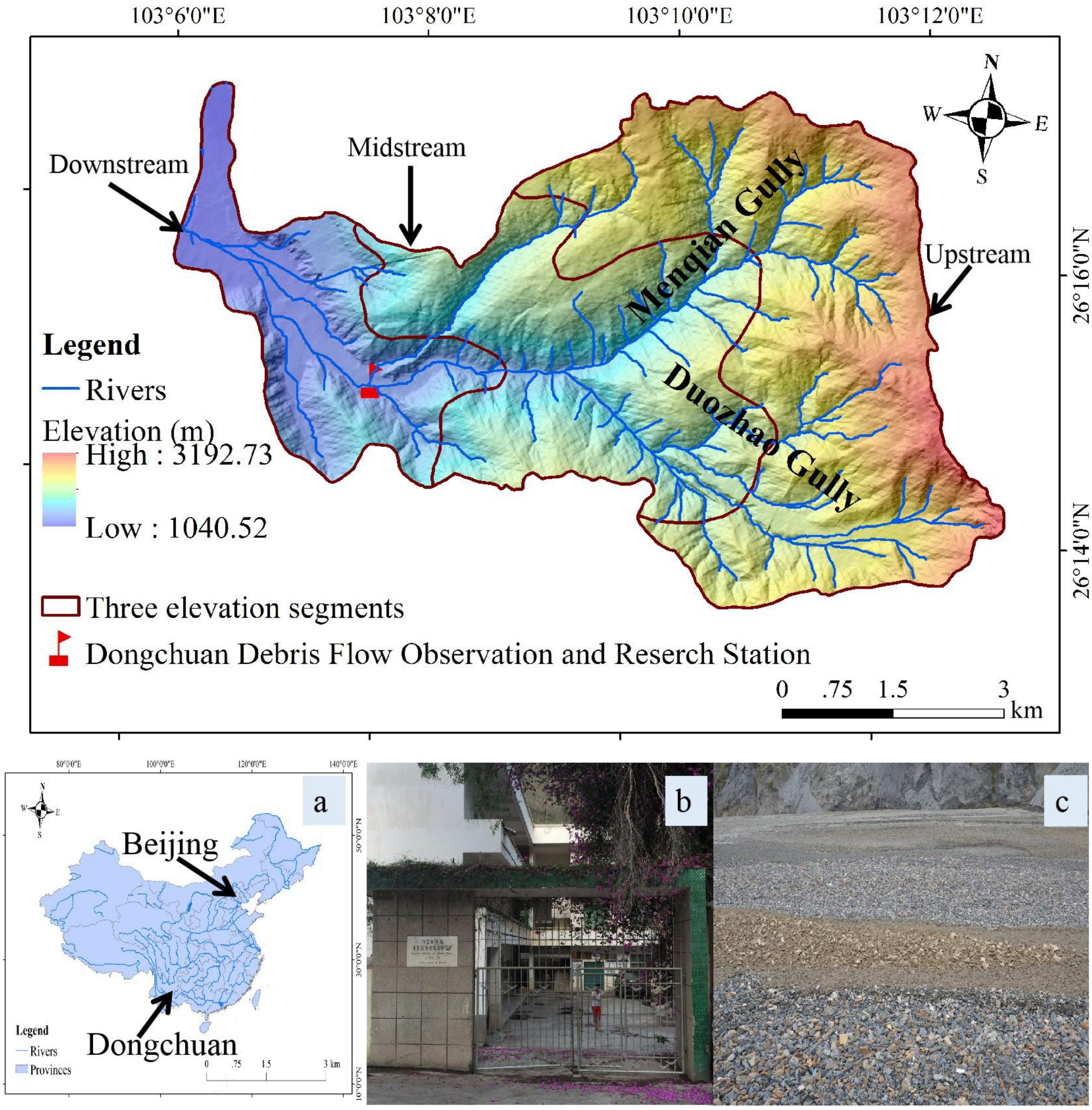

Fig. 1 The location of JJG. a The location of Dongchuan in China. b Dongchuan Debris Flow Observation and research stations. c Deposition of surges.

2.2 Data collection

2.2.1 The tributaries divided in JJG

Digital elevation model with spatial resolution 10 m is used in this study to generate elevation and area information, which was purchased in the Sichuan surveying and mapping bureau. 81 tributaries are abstracted from the watershed of JJG. The tributaries are divided based on field investigation result that each tributary is a complete unit for observable landslides and debris flows, also according to the fact that debris flows are prone to occur instead of direct extraction based on the same water collection threshold. In other words, these tributaries are all conspicuous in surface mass movement and loose materials are distinguishable on its slope. The tributaries are extracted from the DEM using GIS tool and also with artificial correction to ensure the accuracy of boundaries (now it is Fig. 3). In principle, the gully can be divided further into smaller tributaries, but that makes little difference for the present purpose as to distinguish tributaries. Some tributaries in field are displayed in Fig. 2, obviously, there are significant differences among these tributaries The tributary area varies between $8.7 \times 10^4 \sim 2.07 \times 10^6$ m^2 and cover a total area of 4.62×10^7 m^2, about 95% of the whole gully. The serial number of tributary in subregions is presented in Table 1.

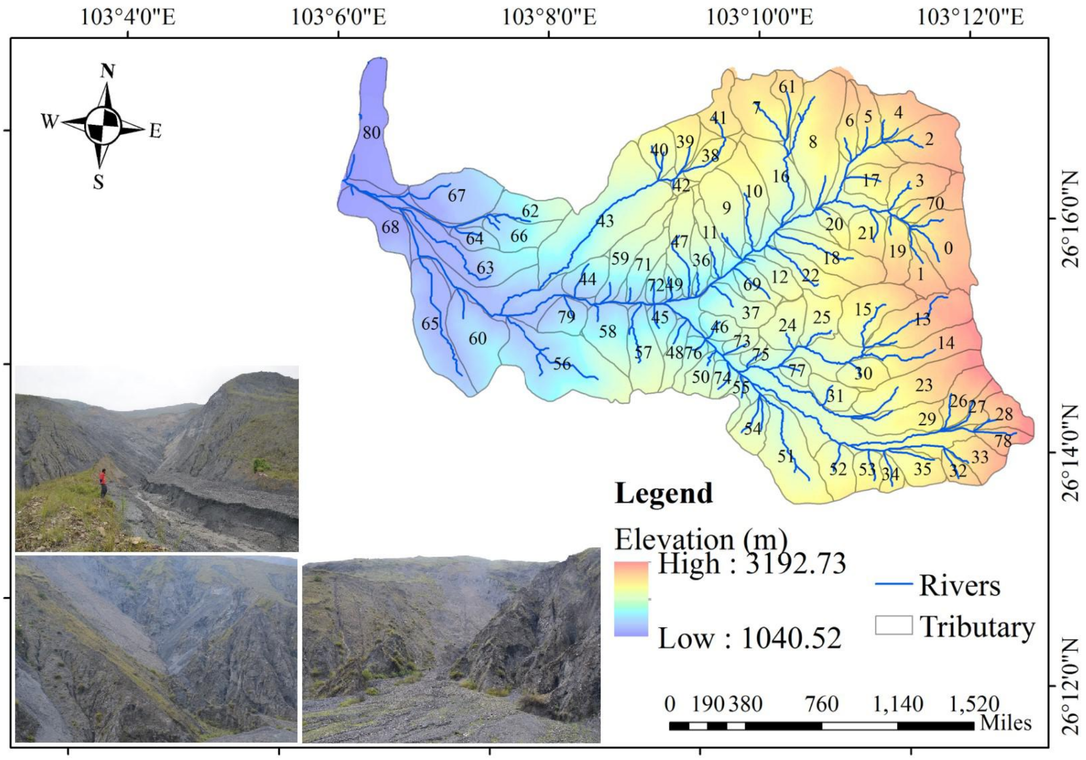

Fig. 2 The tributaries divided of JJG. Some tributaries in the field are shown on the map.

Table 1 The tributaries distribution in subregions.

Subregion	The No. of tributaries
Menqian Gully	2, 4, 5, 6, 7, 8, 9, 10, 11, 12, 16, 17, 18, 20, 22, 36, 37, 47, 49, 61, 69
Duozhao Gully	13, 14, 15, 23, 24, 25, 26, 27, 28, 31, 32, 33, 34, 35, 45, 46, 48, 50, 51, 52, 53, 54, 55, 73, 74, 75, 76, 77, 78
Upstream	0, 1, 2, 3, 4, 5, 6, 7, 8,10, 13, 14, 15, 16, 17, 19, 20, 21, 23, 26, 28, 29, 30, 32, 33, 34, 35, 38, 39, 40, 41, 42, 61, 70
Midstream	9, 11, 12, 22, 31, 36, 37, 43, 45, 46, 47, 48, 49, 50, 51, 54, 55, 59, 69, 71, 72, 73, 74, 75, 76, 77
Downstream	44, 56, 58, 60, 62, 63, 64, 65, 66, 67, 68, 79, 80

2.2.2 The hypsometric curve and EI

Hypsometric curve for each tributary is calculated. The hypsometric curve is generated by plotting the relative area along the abscissa and the relative height along the ordinate. The relative height can be obtained as the ratio of the height of a given contour (h) from the base plane of the stream mouth to total height of the tributary with reference to the maximum elevation (H), and the relative area is obtained as the ratio of the area above a particular contour (a) to the total area of the tributary encompassing the outlet (A) (Strahler, 1952).

Hypsometric integral is the area between the hypsometric curve (y=h/H and x=a/A) and coordinate axis (Strahler, 1952, 1957), which can be defined as the evolution index (EI).

2.2.3 The extraction of landslides information

Quickbird image of 0.61 m resolution is purchased to create an inventory of landslides. The satellite image is adopted in this study with low cloud shadow coverage, and the aerial coverage of the cloudy area is 0.09 km^2 in the study area, about 0.18% of the gully. The atmospheric correction and radiometric correction have been carried out by using the calibration function within the tools of Envi 5.1 software, and 4, 3, 2 bands are combined to false color image stretched of contrast using standard deviation method. Both landslides number and landslides area are necessary to interpret, so the equal area projection is adopted, which has less impact on the landslides area. The landslides information becomes easily extracted on the source image after processing, which is beneficial to the work of visual interpretation, and thus ensures the accuracy of the results.

Landslides are mapped from high resolution satellite data acquired using visual image interpretation on Arc GIS 10.3 software with false color composites or panchromatic images uniformly on 1:5000 scale. The individual landslides initiation zones are indicated using polygons. In the case of complex situations where many landslides are interconnected, it is difficult to identify the individual initiation zones. Use of high resolution images enables demarcation of clustered landslides as individual polygons. The minimum size of landslides area extracted is determined as 253.26 m^2.

In the interpretation process, we make use of the following diagnostic features: the tone, texture, pattern and shape or form. Meanwhile, direct method, comparison method, integrated reasoning method and other synthetical methods are always used (Dai and Lee, 2002; Kumar et al., 2017; Valenzuela et al., 2017). Using the methods above, 906 landslides have been identified, with area ranging of $2.53 \times 10^2 \sim 6.7 \times 10^5$ m^2. In addition, fieldwork was carried out in May and June 2017. We investigated the location and area of 100 landslides distribution with the GPS instrument, and the accuracy achieves 89.21%. The LA (landslides area) and LN (landslides number) is obtained, they are used to analyze the relationship between EI with LA_p and LD of each tributary, of which LA_p is landslides area in a tributary/ the tributary area (%) and LD is landslides number in a tributary/ the tributary area (/10^6 m^2).

3 Evolution division of JJG

3.1 Hypsometric analysis

The hypsometric curves for tributaries are shown in Fig. 3:

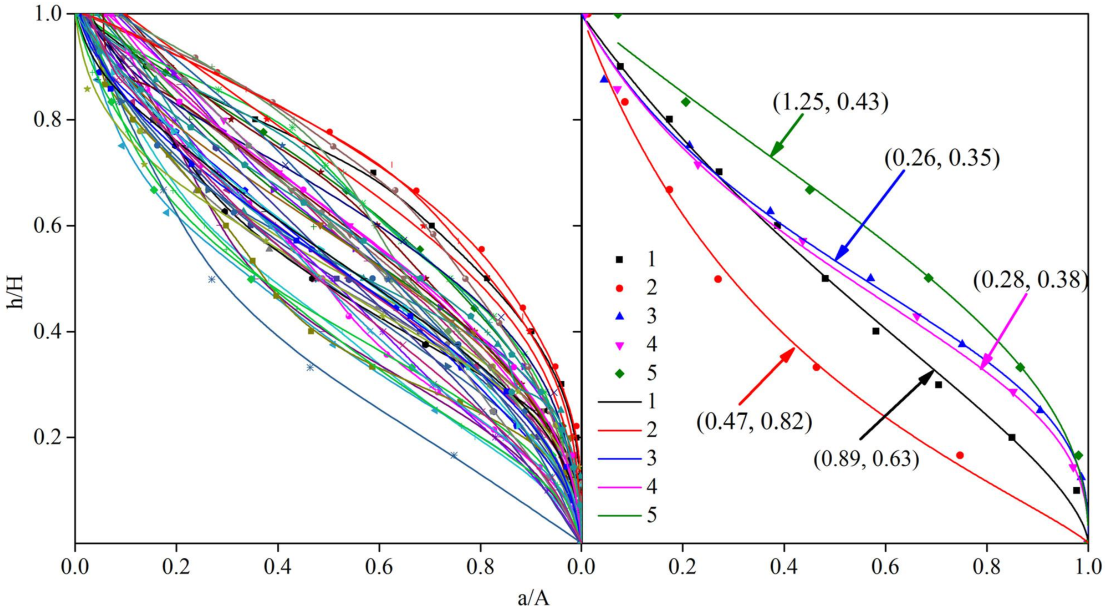

Fig. 3 The hypsometric curves of different tributaries.

The curves present various types, such as convex, concave and others between them; and these can be well fitted by the following function (Strahler, 1957):

$$y^{1/n} = k(1-x)/(x+k) \quad (1)$$

Where k and n are parameters, with the fitting coefficient R^2 of 0.90 and higher. It is found that higher the curve is, greater the k is. Meanwhile, the curve is rising as n decreases.

3.2 Evolution division of JJG

Then the EI of each tributary in JJG is calculated, which varies from 0.32 to 0.84. According to Strahler, there are three stages: inequilibrium or youthful stage (EI > 0.6), equilibrium or mature stage (EI between 0.3 and 0.6), and monadnock or old stage (EI < 0.3) (Strahler 1952). In order to distinguish the evolution differences of the tributaries, we conduct a more detailed classification and the EI of tributaries in JJG are divided into five groups (Fig. 4):

I (< 0.45), appears in downstream areas and near the outlet of the gully;

II (0.45-0.55), occurs mostly in the Duozhao Gully;

III (0.55-0.65), mostly distributes in midstream and downstream;

IV (0.65-0.75), mostly in midstream and upstream;

V (>0.75), mainly distributes in the headwaters of the Menqian Gully;

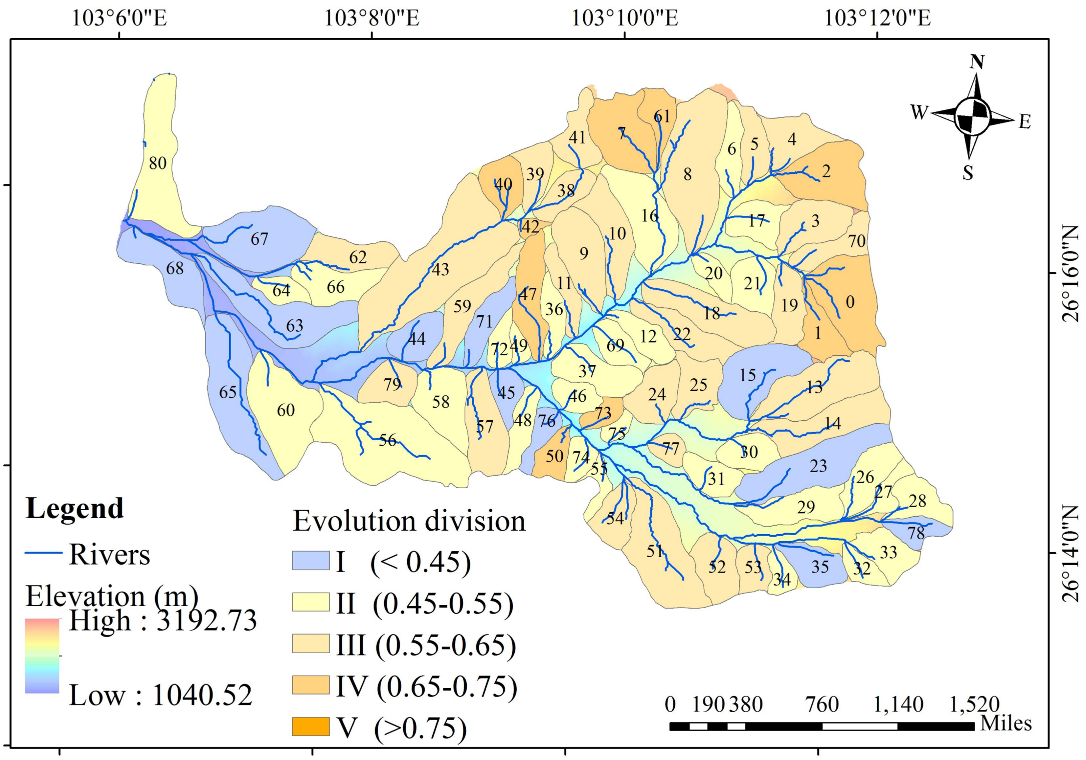

Fig. 4 The evolution division and EI distribution of tributaries in JJG.

Moreover, it is found that the EI satisfies the Weibull distribution with the scale parameter of 0.02 and the shape parameter of 1.69 (Fig. 5). The small value of scale parameter means that EI is much concentrated and EI of most tributaries in JJG is mainly between 0.5 and 0.6. The shape parameter is more than 1 and the frequency of the tributaries changes rapidly with the increasing of the EI, indicating that there is a great difference among the active tributaries. According to the frequency distribution of EI, the tributaries of JJG is generally in mature and youthful evolution stages, that is the reason why high frequency debris flow occurred in JJG in the past several decades.

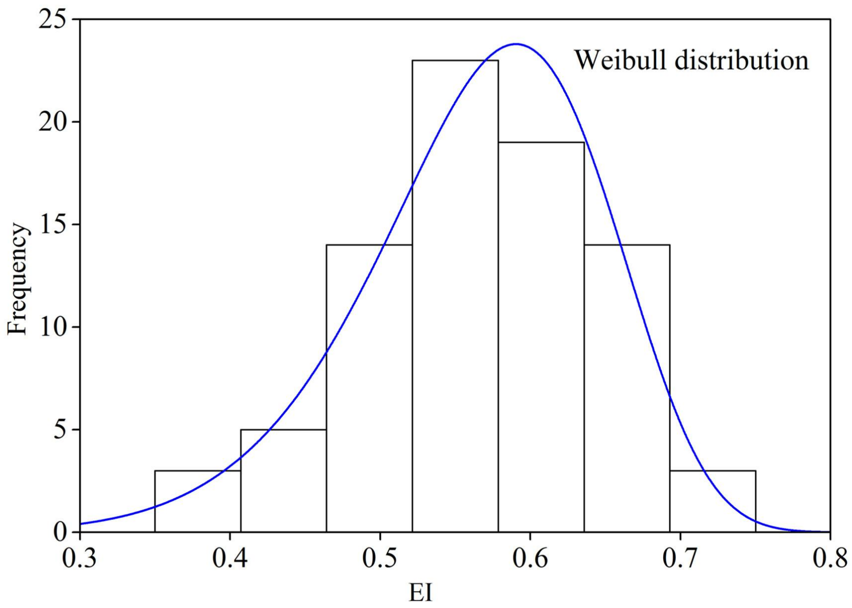

Fig. 5 The frequency distribution of EI for tributaries in JJG.

3.3 Inflection point of hypsometric curves

Obviously, the hypsometric curves exhibit different shapes, which can be featured by the inflection point, defined as the zero point of the second derivative of the fitting curve (Eq. 2):

$$y''=\frac{nk^{n}(k+1)(2x+k-nk-n-1)(1-x)^{n-2}}{(x+k)^{n+2}} \qquad (2)$$

where x denotes a/A, and $y''=0$ determines the inflection point at a/A_{ip}. It is found that the a/A_{ip} varies with EI in a power law form (Fig. 6), meaning that the bigger the evolution index is, the lower the inflection points of the curves are. The higher the EI value, the lower the inflection point, and this implies that there should be more material accumulated in the lower part of the tributary, which are relatively easy to join the the debris flow.

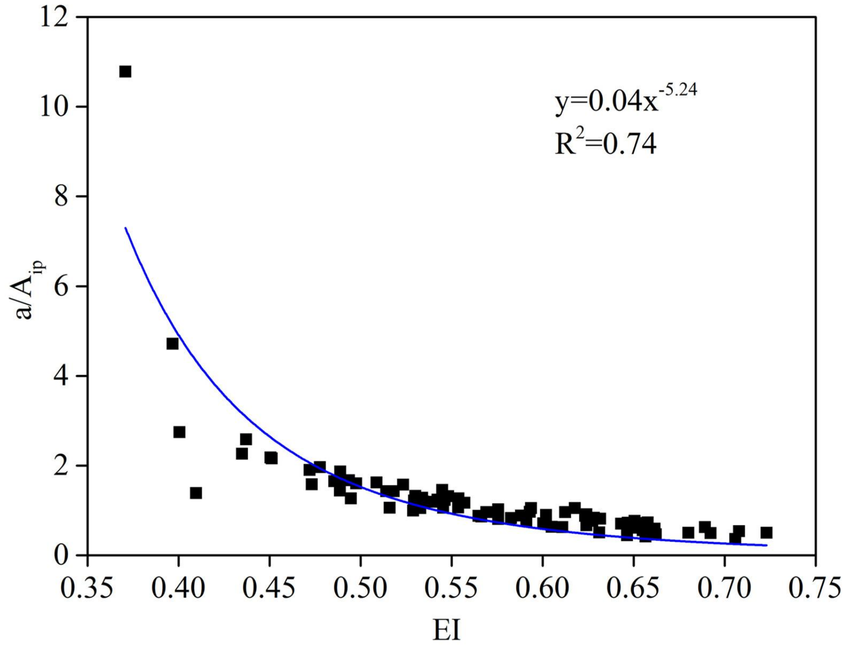

Fig. 6 The relationship between the inflection point and and EI.

Moreover, we display the hypsometric curves of different evolution stages in Fig. 7; in particular, the inflection points of the curves (the rectangle in each plot) are displayed in different position of the curves. The inflection point indicates the elevation of a tributary with area varing. It can be seen in Fig. 7 that the larger of the EI is, the smaller of the a/A_{ip} is. When the point is high, the changing occurs at the high elevation, i.e., mainly in the upstream of the tributary. Since there is no evolution area more than 0.75 in JJG, four major evolution divisions are analyzed.

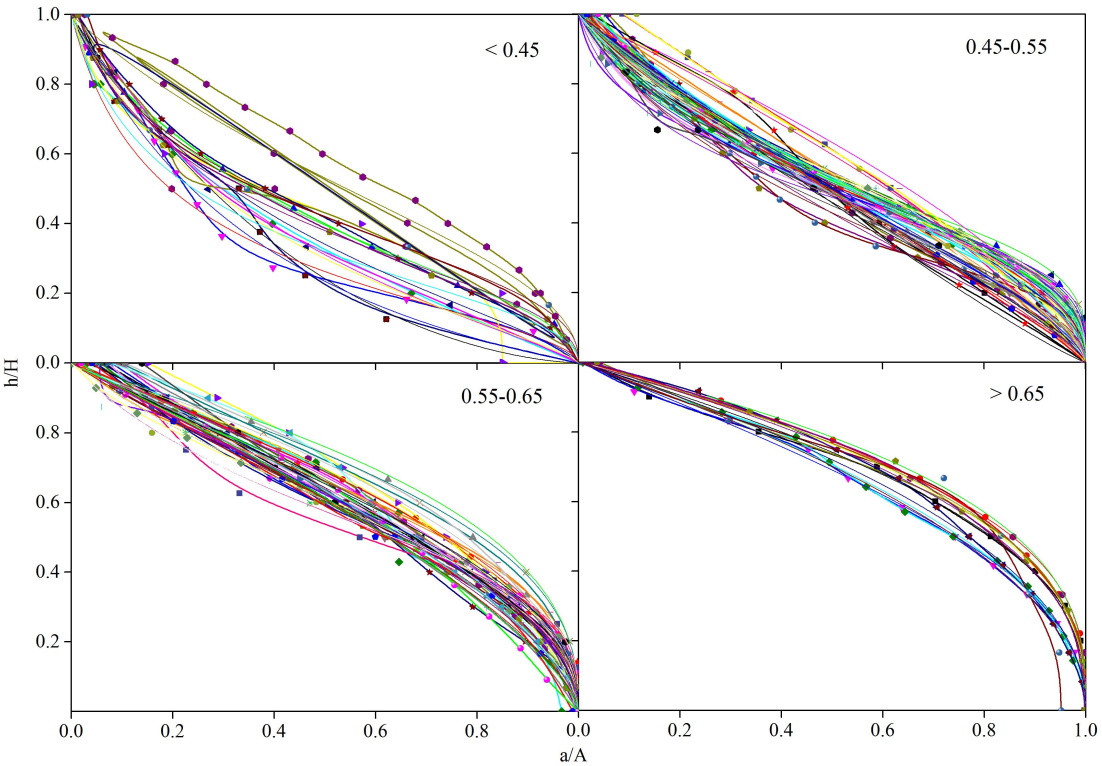

Fig. 7 Hypsometric curves of different EI divisions

The evolution curve changes from concave to convex with the increasing of evolution value, and the convex form of the tributary is more conductive to the material movement of the tributary and more loose materials are produced.

For a given elevation of point, larger area above means that more material are concentrated. For example, inflection points in EI between 0.45~0.55 are generally higher than those in EI below 0.45, indicating that more material concentrates in such tributaries, which are more prone to debris flow activities. Correspondingly, the lower the hypsometric curve is, the more concave the curve is presented, and the smaller the a/A_{ip} is, which indicates that the elevation changing in unit area is small, such a tributary is not conductive to the occurrence of landslides and debris flow activities.

Some landslides distribution of tributary in different evolutionary periods is shown in Fig. 8. In the tributary within the EI range of 0.35-0.45, the landslides distribution is scattered with the large area and low number, and the tributary is generally concave, which is not conductive to the materials movement. In addition, with the increasing of the evolutionary value, the landslides number is increasing and the area is decreasing, and the tributary in high EI division is convex, which is conductive to the materials movement.

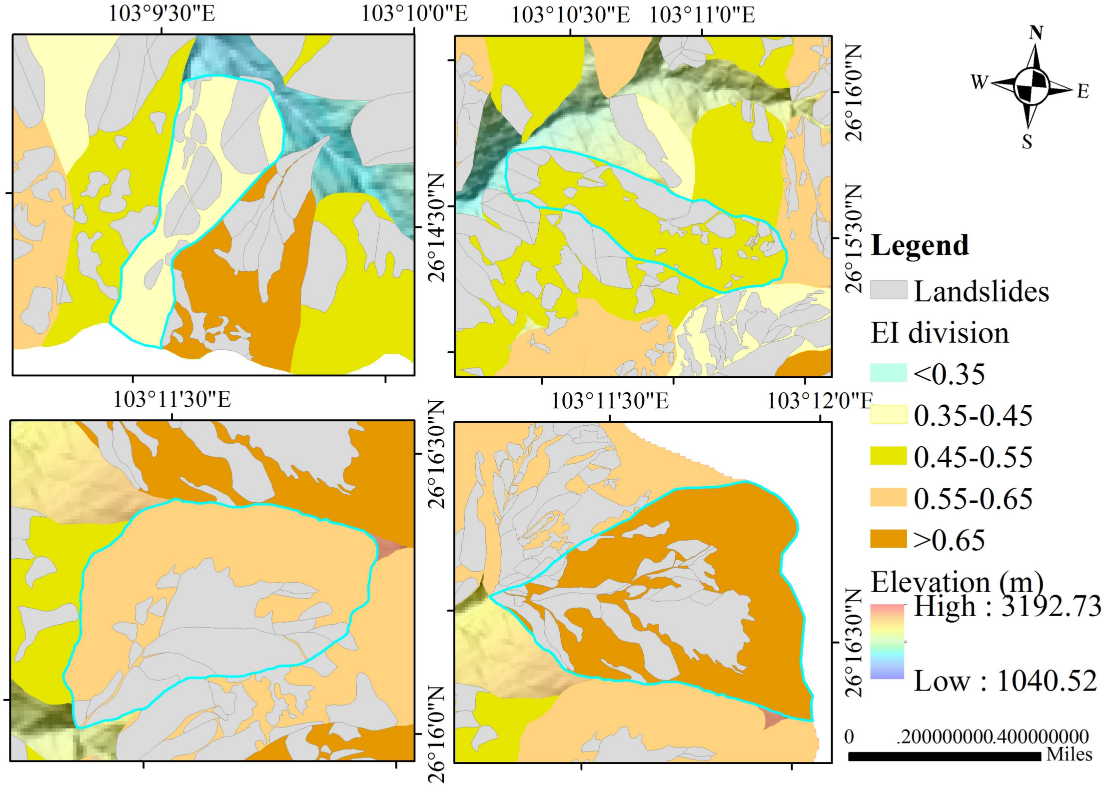

Fig. 8 Some landslides distribution tributaries of different EI divisions

4 Landslides distribution in relation to EI

4.1 Landslides distribution of JJG

A total of 906 landslides have been identified, with area ranging from 2.53×10^2 m^2 to 6.7×10^5 m^2. The spatial distribution of landslides is shown in Fig. 9.

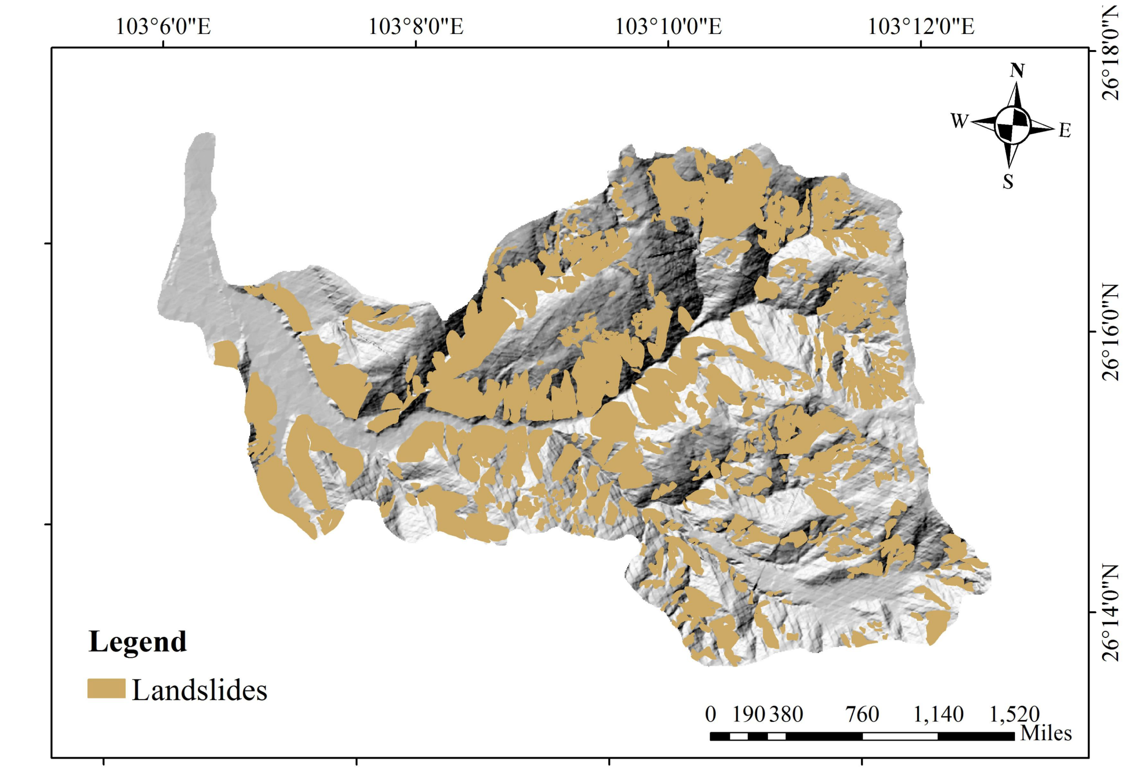

Fig. 9 Spatial distribution of landslides in JJG.

Landslides are mainly distributed in both sides along the mainstream channels. In details, landslides in Menqian Gully are more concentrated while in Duozhao they are scattering, which is consistent with field observations that landslides are always more frequent in clusters in vulnerable areas.

The landslides distribution in subregions is shown in Table 2. The area of the Menqian gully is smaller than Duozhao gully, the total area and number in Menqian gully is 4.78 km^2 and 274, respectively which is more than Duozhao gully with area 4.18 and number 232. In adddition, LA_p and LD in Menqian gully is more than in Duozhao gully. Since the area of the upstream is the largest and smallest in downstream, it is meaningless to compare the absolute value of the landslides. Now LA_p and LD in these segments is compared, and LA_p and LD are both greatest in upstream and smallest in downstream.

Table 2 The landslides distribution in subregions.

Subregion	The area (km^2)	The area percentage (%)	Landslides			
			LA (km^2)	LA_p (%)	LN	LD (km^{-2})
Menqian Gully	10.51	21.72	4.78	45.51	274	26

Duozhao Gully	11.16	23.05	4.18	37.51	232	21
Upstream	16.84	34.80	7.23	42.90	440	26.15
Midstream	10.48	21.65	4.13	39.40	261	25
Downstream	9.71	20.07	3.59	36.91	106	10.90

4.2 Landslides distribution in different evolution division

4.2.1 The landslides distribution related to evolution stages of all tributaries

The evolution division and landslides distribution layers are overlaid to form the spatial distribution map, as shown in Fig. 10. It is clear that major of landslides are distributed in subregions of III and IV, with EI between 0.55 ~ 0.75.

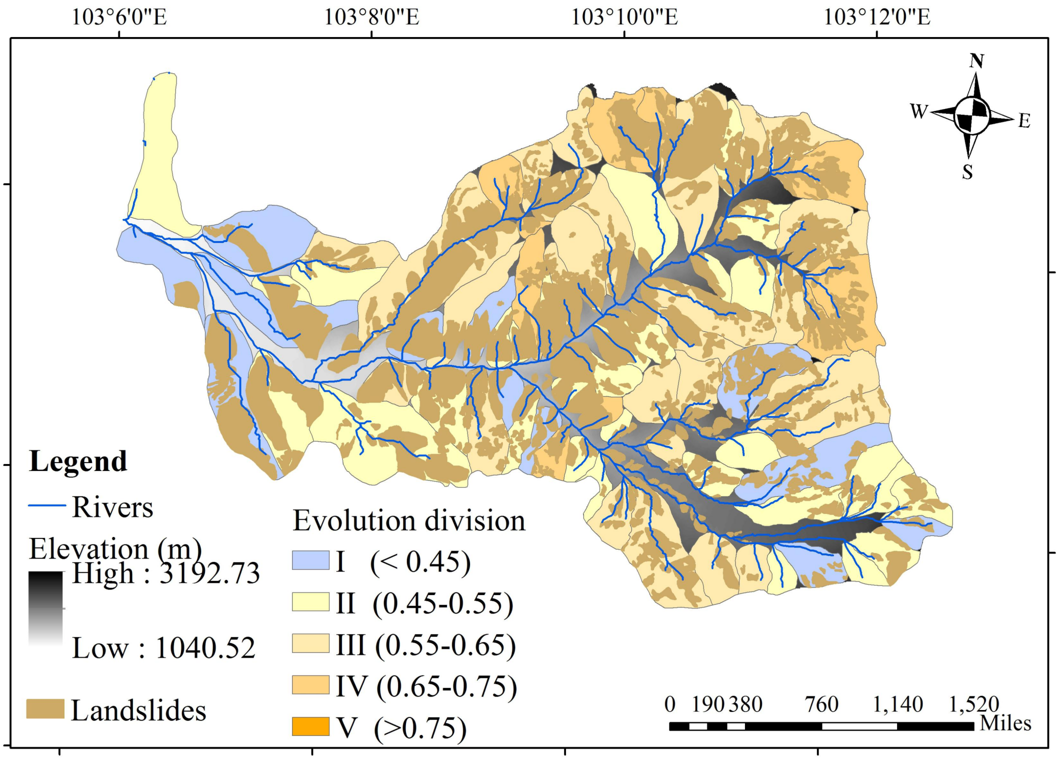

Fig. 10 Landslides distribution in various evolution stages.

Fig. 11 shows how LD and LA_p vary with EI. It shows that LD increases exponentially with EI increasing, which means that more landslides occur in the tributaries at younger stage. Meanwhile, the greater fluctuation of LA_p is in tributaries with the range of EI less than 0.55, while a smaller fluctuation is in tributaries of EI more than 0.55, and the LA_p is generally smaller than other evolution stages in active evolution stage.

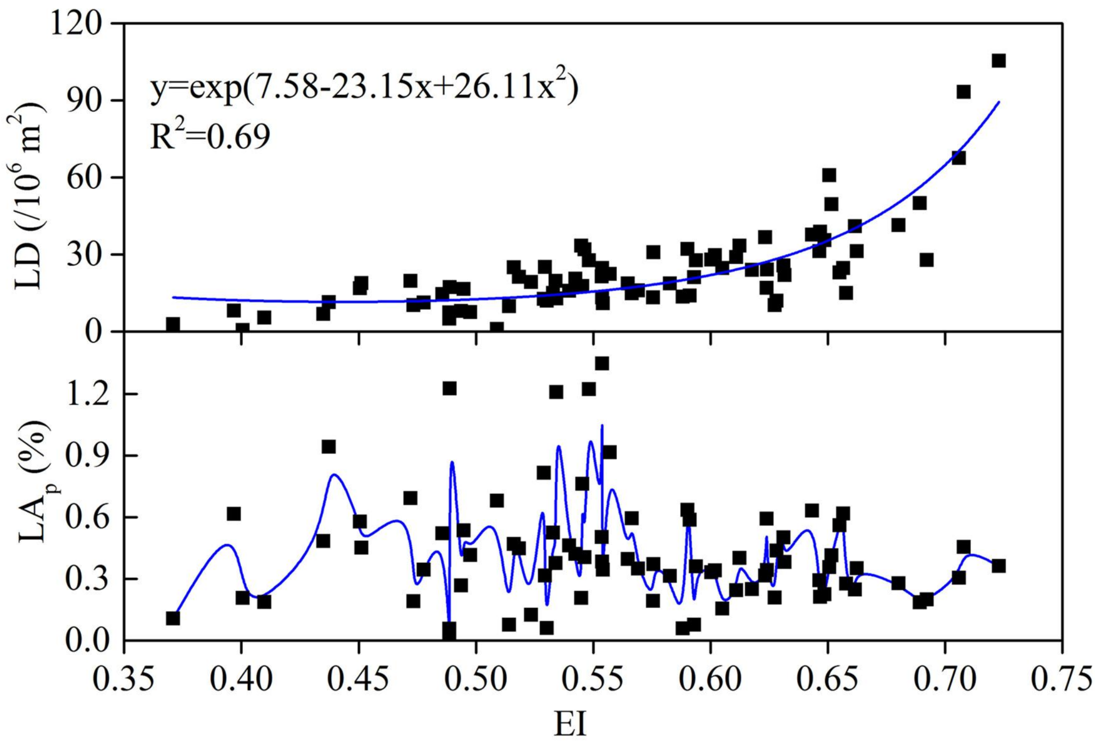

Fig. 11 Relationship between landslides and EI.

4.2.2 Landslides distribution in typical subregions

The major branches of JJG, the gully of Menqian and Duozhao, are distinctive in debris flow and landslides activities. As mentioned above, landslides are more scattering in Duozhao and more concentrated in Menqian. Now we consider how landslides distribute in tributaries in these subregions.

Fig. 12 shows that in both gullies LD increases exponentially with EI, almost in the same exponential function. As for LA_p, several peaks occur in different EI values in Menqian Gully but only a single peak occurs (around EI with 0.55) in Duozhao Gully, meaning that landslides are widely distributed in tributaries with EI >0.45 in Menqian Gully.

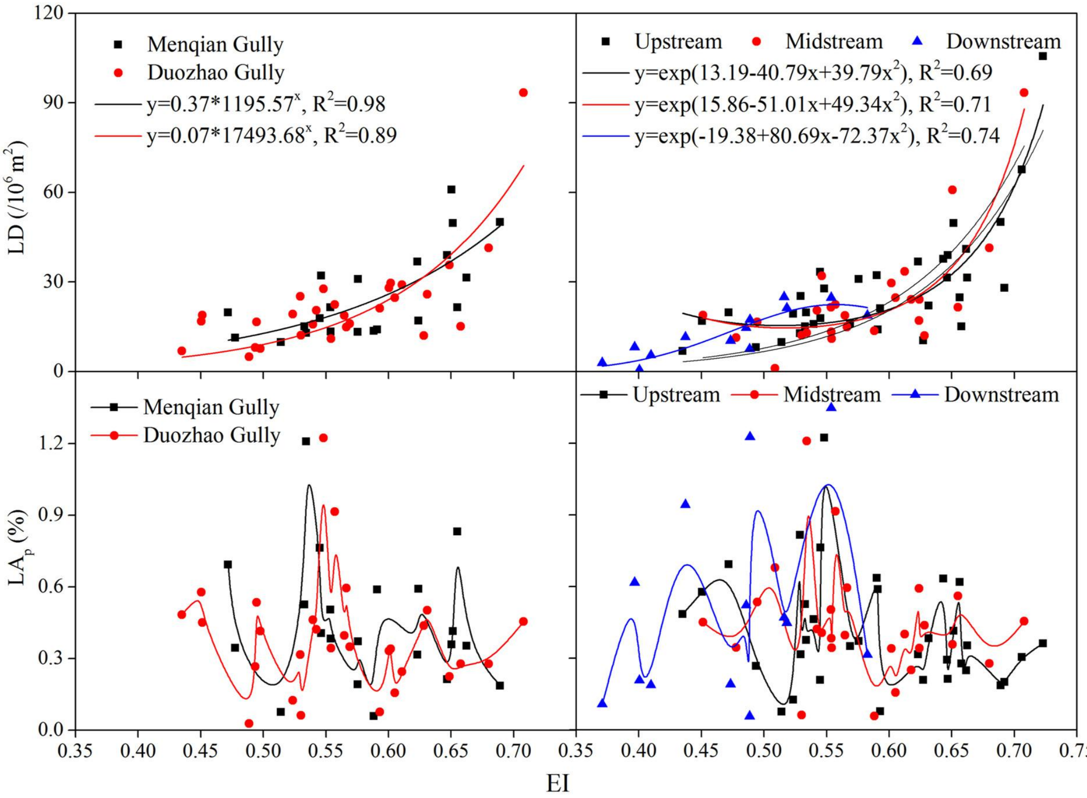

Fig. 12 Relationship between landslides and EI in subregions.

Similarly, we consider LD and LA_p in the regions of the upstream, midstream and downstream in JJG that have visible terrain difference, as shown in Fig. 12. Again it is found that LD increases exponentially with EI both in the upstream and midstream.

LA_p mainly increases first and then decreases as EI increases, and the LA_p-EI curve in the range of less than 0.54 is higher than the range of more than 0.54, which has the similar tendency with the LA_p-EI curve in all tributaries of JJG. Also the LA_p in upstream and midstream is higher than upstream, lower LA_p exists in tributaries at the younger evolutionary stages. Meanwhile, lower LD and larger LA_p is in the downstream, which is at the old evolution stage, which means that with the occurrence of historical landslides or large landslides in slope surface, the tributary has reached a stable state.

5 Discussion

5.1 The Power-law distribution of landslides

Power-law frequency-magnitude relationship has been generally observed for landslides at a wide range of size (Hovius et al., 1997; Stark and Hovius, 2001; Malamud et al., 2010), but for a small-scale gully like JJG there is no report in literatures. For the landslides in JJG, the power law is perfectly valid (Fig. 13), with exponent being -1.45, which differs much from the exponent for landslides over large scale regions, such as those in the Gorkha area (2.5), the Northridge, California (2.30), and the Wenchuan area (2.19), and many other regions (Eeckhaut et al., 2007; Lari et al., 2014). The verification of power law confirms that the landslides area interpreted is reliable.

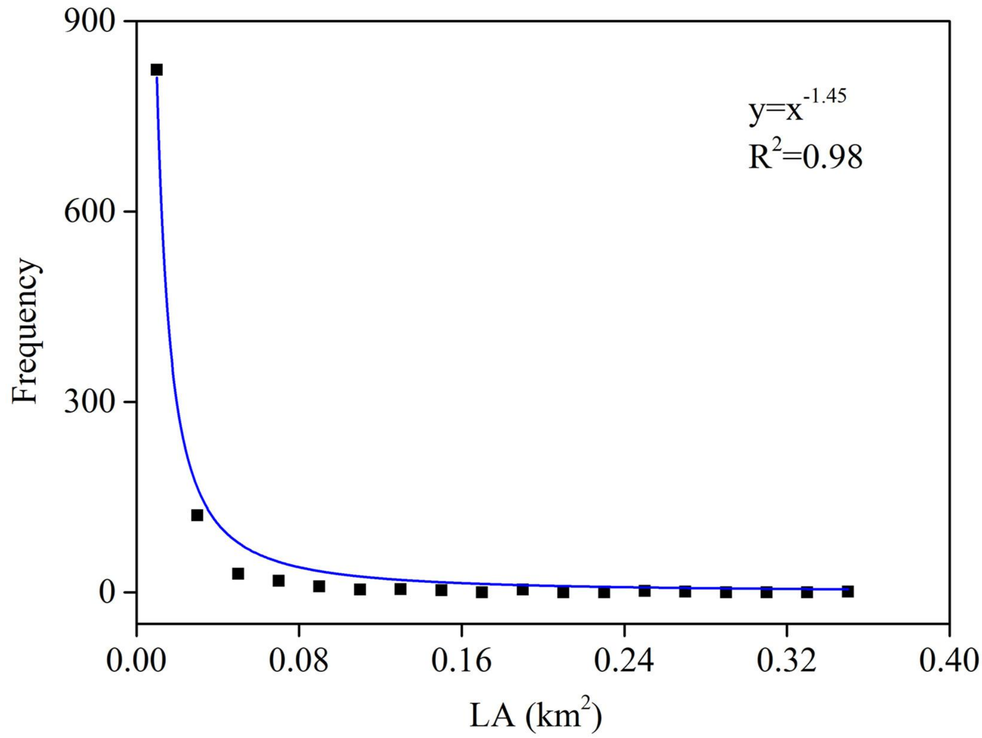

Fig. 13 The landslide area frequency distribution of JJG.

5.2 EI and tributary morphological feature

As a comprehensive topography index, EI reflects the geomorphology characteristics of the tributary. Fig. 14 shows how slope varies with EI on average, as it is crucial for landslides and debris flow formation. The maximal average slope, usually bigger than the friction angle of the soil, occur mainly between EI of 0.5-0.65, this coincides with range of most landslides distribution, and this also accounts for the relationship between EI and LD which indicates that EI is related to the number or frequency of landslides. Meanwhile, the landslides are concentrated in tributaries of class III (EI = 0.55~0.65), and these tributaries are concentrated in the midstream and upstream, mainly in the Menqian Gully. The landslides distribution in tributaries of different EI quantitatively reveals spatial heterogeneity distribution. The spatial distinction of landslides distribution results from the diverse evolution stages of tributaries, which provides a heterogeneous background for material supplying in gully. The spatial heterogeneity distribution can reveal the reason why landslides are frequent in some tributaries while occasional in others, thus roughly to predict the landslides activity of tributaries, which is of great significance to the comprehensive management of small watershed.

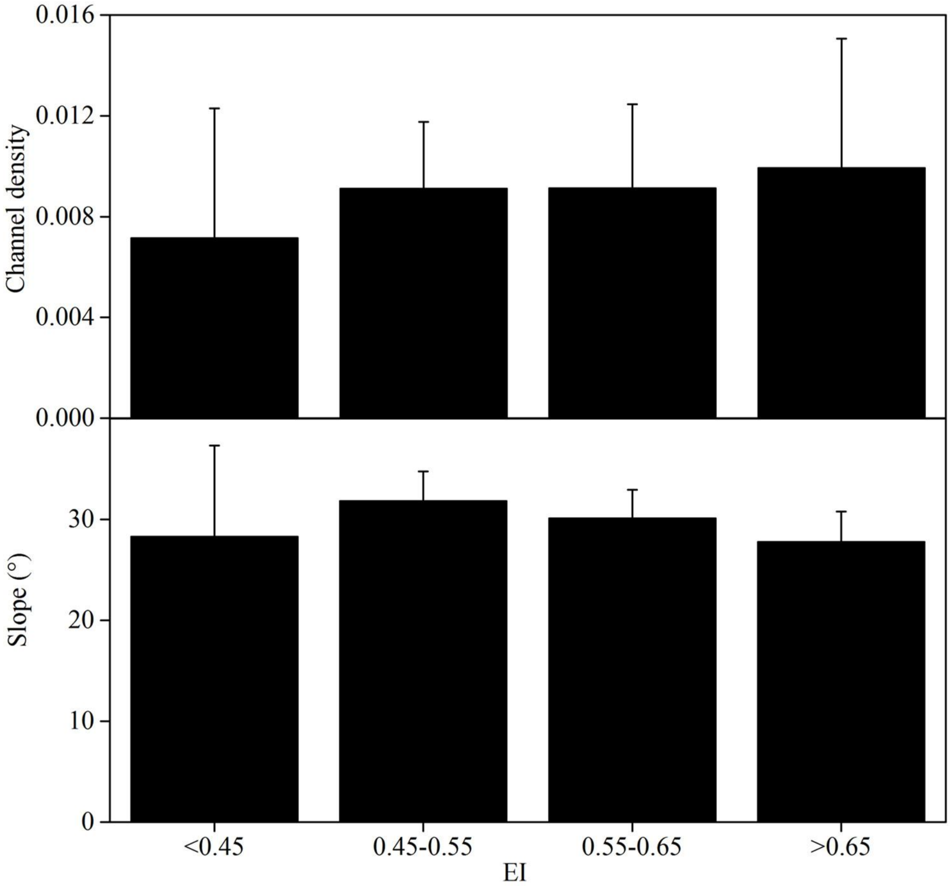

Fig. 14 The variation of the tributary morphological feature in different evolution stages.

Debris flow converging from tributaries into mainstream channel depends on the flow routes, or the stream length of each tributary, and this can be described by the channel density (i.e., the length in unit area of a region). Fig. 15 shows the density variation with EI, indicating that the channel density of tributary is increasing as EI rises, which is conducive to the occurrence of debris flow activity.

Then the tributaries of EI between 0.5 and 0.65 provide favorable condition both for landslides and flow convergence, and thus facilitate the forming and developing of debris flows.

5.3 Implication in debris flow surges

The most remarkable features of debris flow in JJG are the high frequency in occurrence and great variety of flow regime and magnitude. Each occurrence contains tens to hundreds of surges (Li et al., 2012); the surges are separated in time and space, and different from one another in density, velocity, and sediment concentration. The variation of flow velocity with density is shown in Fig. 15, which contains surges in one single event on July 12, 2017.

The great variety of surges densities, with different material compositions, can be attributed to different sources; this means that even a single surge material comes from different tributaries in most cases (Webb et al., 1989). As observed in the last decades, debris flows almost come from the north branch, the Menqian Gully, while the south branch, the Duozhao Gully, is often silent. This presents the gross distinction of material and landslides activities in JJG, which further implies that there must be more differences in tributaries.

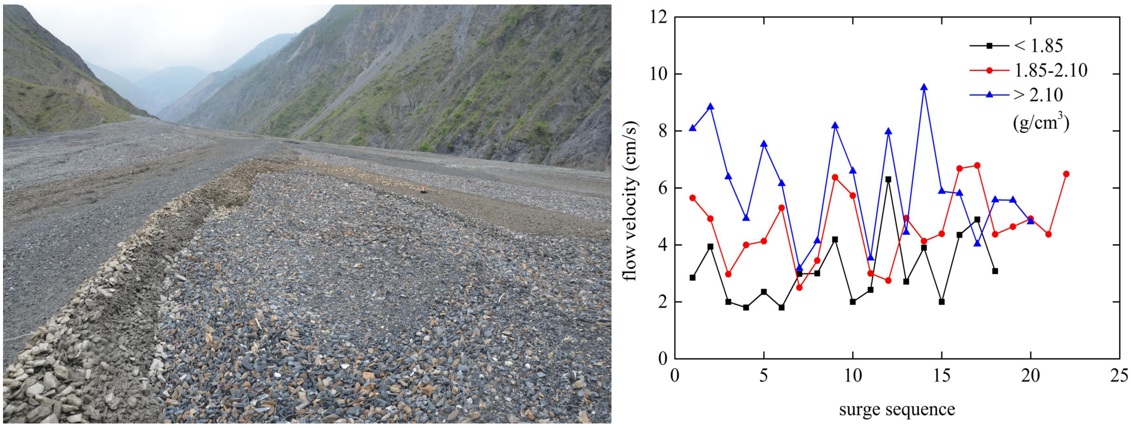

Fig. 15 Debris flow surges deposit in the mainstream of JJG.

The spatial heterogeneity of tributary distribution reveals the variety of debris flow sources. As it is difficult to observe the debris flows of each tributary, we usually see the convergence debris flows from multiple sources. Debris flow surges always present the characteristic of diverse forms from the perspective of material supplies (Li et al., 2015), and this can be attributed to the spatial heterogeneity of evolution and landslides activity of tributaries as discussed above.

Previous studies usually consider debris flows activity on the gully scale and ignore the distinction on tributary scale (Chen and Wang, 2017; Malet et al., 2004), they cannot tell the feature of debris flows from multiple sources and undergoing diverse tributaries processes, such as initiation on slope, flow downwards in tributary channel, and confluence into the mainstream, all closely related to the tributary feature.

Besides, the formation of debris flow is activated by rainfall (Chen et al., 2006; Fuchu et al., 1999; Fusco et al., 2017; Kuo and Chuan, 2007; McArdell et al., 2007; Reneau and Dietrich, 1987; Tan and Han, 1992), different rainfall intensity and amount is in different tributaries, which adds more diversity to the surges. The factor of precipitation will be the next study to consider and understand the formation mechanism of debris flow surges.

5.4 General application of EI for landslide source identification

The case study in JJG provides a relationship between EI and landslides distribution; the traditional methods make a comprehensive analysis of various influencing factors of landslides (Amashi et al., 2019; Baena et al., 2019; Ciurleo et al., 2019; Hu et al., 2019; Rao et al., 2017; Singh et al., 2019; Xie et al., 2015), ignoring the landslides distribution mechanism itself, while this paper focuses on the analysis of the landslides distribution state itself in tributary, so this method can be generally applied to identify landslide sources in more general cases. For example, the Wenchuan earthquake has about 11,000 individual landslide points (Gorum et al., 2011), and it is found that these landslides are distributed mainly in relatively high EI tributaries (Tian et al., 2019; Xiang et al., 2015). The EI values for the landslide sources are also subject to the Weibull distribution (Fig. 16), which is similar to the case of JJG. In comparison, in JJG, EI of tributaries satisfies the Weibull distribution with the scale and shape parameter for JJG case are respectively of 0.02 and 1.69, while for, this is comparable to the EI distribution of tributaries in the Wenchuan region where the scale and shape parameter is 0.53 and 11.73, respectively. The scale parameter can reflect the EI range of variation, which varies between 0.38 and 0.64 in the Wenchuan area and betweenem 0.37 and 0.73 in JJG. The difference here can be attributed that a number of tributaries in JJG having no landslides, while in Wenchuan, only tributaries having landslides distribute in almost every tributary are taken into account, which means the concentration of EI. This also implies that landslides occur in tributaries within a relatively narrow range of EI. More important point is the difference between shape parameters, the bigger shape parameter in Wenchuan region means that the curve is to the right more than in JJG, implying that the earthquake is inclined to induce more landslides in tributaries of big EI. As JJG is of tributaries with wide range evolution stages, we choose it as the study area to reveal the mechanism of landslides distribution.

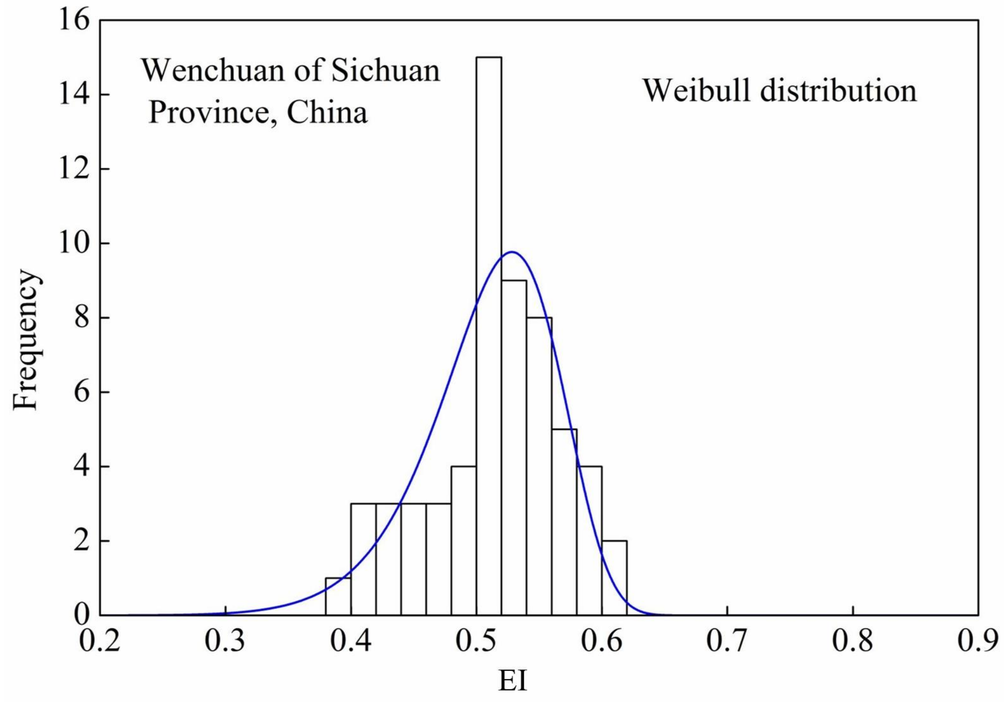

Fig. 16 The EI frequency distribution of Wenchuan in Sichuan province.

6 Conclusions

This study has revealed the spatial heterogeneity of landslides distribution in tributaries of different evolution stages. It is found that most landslides are distributed in the relative young tributaries (with evolution index between 0.5 ~ 0.6). Generally, the LD increases exponentially with EI and the LA_p is concentrated in EI between 0.5 and 0.6, in accordance with the general landslides distribution. The spatial heterogeneity of landslide distribution provides the background for the high variety and intermittency of debris flows in JJG.

Meanwhile, the EI satisfies the Weibull distribution, such distribution feature also occurs in the tributaries of landslides induced by the Wenchuan earthquake. This implies that the EI can be taken as an indicator for identifying landslide sources in mountainous watersheds.

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