



# Response analysis of valley settlements to the evolution of debris flow fans under different topographic conditions: a case study of the upper reaches of Min River, China

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Received: 23 March 2019 / Accepted: 16 October 2019 / Published online: 16 November 2019  
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## Abstract

The upper reaches of Minjiang (Min) River were selected to research the relationship between debris flow fan formation and topography. Combining the historical statistical data of settlement and debris flow events, there are 3 years (1994, 2004, and 2014) for which comparable data are available. With the support of remote sensing (RS) and geographic information system (GIS) technology, the distribution characteristics and evolution of valley settlements and debris flow fans in terrain conditions with varying elevation, slope, and slope aspect are analyzed. The coupled relationship between valley settlement and debris flow accumulation fan evolution is analyzed by regression analysis. The results show that the distribution characteristics of valley settlements and debris flow fans in the upper reaches of Min River show high consistency and convergence in different topographic conditions, and they have a response relationship with each other. With elevation, both settlements and debris flow fans increase linearly with each other, and, over time, the rate of change of the distribution of valley fans with debris flow accumulation increases then decreases. In regard to slope, both parameters conform to two polynomial function models, that is, the river valley settlement increases first and then decreases with the increase of debris flow accumulation fans. For the slope aspect, the number of valley settlements increases with the increase of the change rate of debris flow fans density. The study will provide some assistance for the countermeasures on valley settlements to the evolution of debris flow fans in the upper reaches of Min River.

**Keywords** Valley settlement · Debris flow fan · Topographic · Distribution characteristics · Evolution process · Response analysis · Minjiang (Min) River

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## Introduction

China is a mountainous country, with rugged terrain covering over two-thirds of its land mass (Deng et al. 2008; Wang et al. 2011). These areas are characterized by complex geographical and geological conditions combined with fragile ecological environments, and are subject to frequent mountain disasters, especially debris flow events (Kang et al. 2004). China's land mass also supports the largest population in the world. More than half of the total population resides in the mountains (including hills), establishing mountain settlements of various sizes with distinctive features (Chen et al. 2007). Invariably, there are debris flows in China's mountain areas every year, resulting in unpredictable degrees of casualties and property losses in local settlements. As a result, the study of debris flow

disasters and their effects on mountain settlements has recently become the focus of scholars (Song et al. 2014; Mao et al. 2014; Ding et al. 2016; Zhang 2017).

Settlements are the essence of human societies. They consist of various buildings, structures, roads, green spaces, water sources, and other elements. And, serving as the residence of human beings, settlements are the space-time units with the closest relationship between human life and the external environment (Chen et al. 2007; Shen 2006). Topography, which reflects variations in the distribution of landforms at the Earth's surface, affects the location, planning, and development of settlements (Diao 1999). Liu (2010) considered the relationship between settlements and topography, using the communities in the Yunlin, Chiayi, and Tainan areas as examples. Utilizing regional natural environment and indigenous site data of different periods, the relationship between the topographic environment and spatial distribution of settlements in different periods was evaluated. Liu concluded that settlement distribution of the indigenous populations is closely related to topography, and settlements expand and migrate with time in different terrains. Zhu et al. (2014a) studied the spatial pattern of rural settlements in Northern Jiangsu Province, finding that the distribution of settlements is highly related to landform, water systems, traffic, and other factors. Among them, topography has the greatest influence on the spatial distribution pattern of rural settlements. In the local area of West Bengal India, Roy and Jana (2015), using the relative height difference, average slope, cutting index, intensity index, and river network density to study the relationship between natural factors and the distribution of rural settlements in an area of West Bengal, India, found that the natural conditions of a region have a major control over the establishment of human settlements. Shinde and Gajhans (2015) considered rural settlements in the Jalgoan area of India, and found that the natural topography, soil, and other factors affect the distribution patterns of settlements. Recently, Liu et al. (2017) studied the distribution characteristics of mountainous settlement niches in the upper reaches of the Min River, finding that settlements tend to be concentrated in the slope of 15–35° (gentle slope), in the aspect of 45–135° (half-sunny slope), 225–315° (half-sunny slope), and 135–225° (sunny slope). Thus, it is concluded that topographic factors such as elevation, slope, and slope aspect (the compass direction a slope faces), play an important role in the size, shape, and spatial distribution of mountain settlements. Still, natural hazards, such as debris flows, also affect the shape and spatial distribution of mountain settlement. Moreover, their development depends on topography by itself.

A debris flow is a type of landslide characterized by a loose collection of mud, sand, rock, soil, water, and air (Fleischmann 1986). It is a common mountain disaster with great destructive power and with the potential to cause

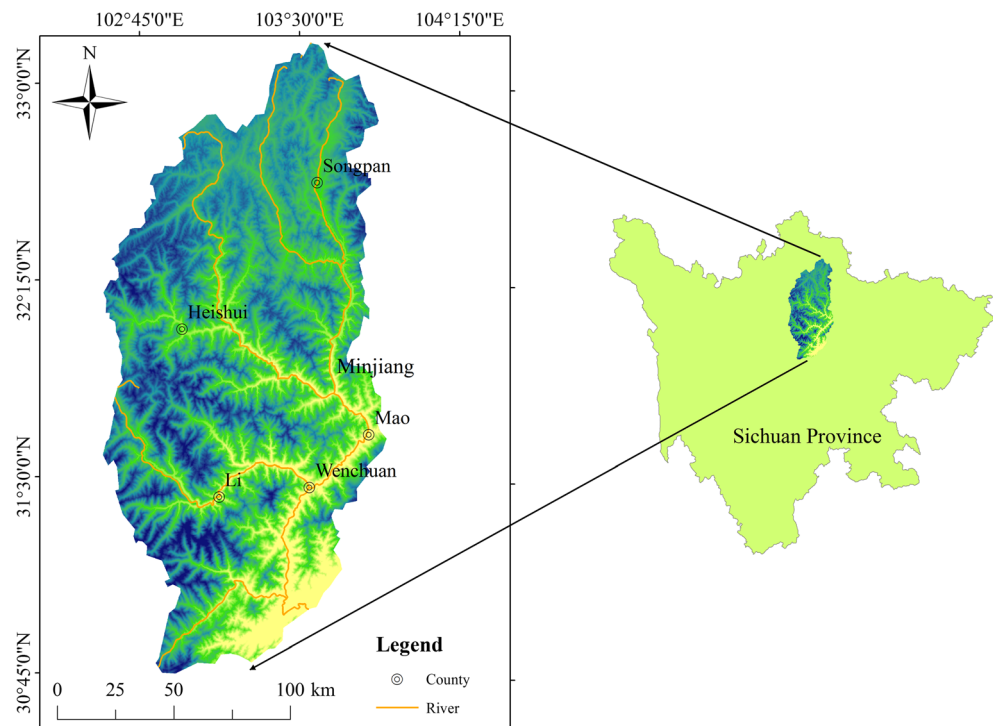
casualties and property loss in a very short time (Li and Yang 1994). The destructive potential of a debris flow is closely related to topography, geological structure, climate, hydrology, and other conditions, with topography serving as the internal cause and necessary condition of debris flow (Fu et al. 1997). When geological and meteorological conditions in a region are approximately constant, topographic conditions become the controlling factors of debris flow (Yu et al. 2011; Ding and Miao 2015). Therefore, the influence of topography on the initiation of a debris flow event should not be neglected. Topographic characteristics that have a large influence on the development of a debris flow include relative height, slope, and slope aspect (Tang and Wu 1990). According to historical data of debris flows in California, Campbell (1975) concluded that the average slope of debris flows is between 26 and 45°. Based on debris flow occurrence data in the Canadian Howe Sound region, VanDine (1985) surmised that the debris flow basin area is generally between 0.4 and 7 km<sup>2</sup>, with an average gully bed slope ranging from 20 to 57°. With the support of remote sensing (RS) and geographic information system (GIS) technology, Larsen and Torres-Sánchez (1998) analyzed the terrain conditions of landslide and debris flow in Puerto Rico, finding that areas prone to disaster have elevation greater than 300 m, slopes greater than 12°, and a slope aspect that is north by northwest. Similarly, Zhu et al. (2014b) took the typical debris flow valley in the upper reaches of Minjiang (Min) River as an example, integrated the three parameters of the form factor, the average slope, the area of formation area into one topographic factor (G-factors), and then discussed the influence of topographic conditions on the development of debris flow. It was found that the larger the valley topographic factor value, the more favorable to the outbreak of debris flow.

This study focuses on the relationship between debris flow fans and valley settlements in the upper reaches of Minjiang (Min) River. With the support of remote sensing (RS) and geographic information systems (GIS) technology, this study builds on previous work by discussing the distribution characteristics of the different terrain conditions such as elevation, slope, and slope aspect. Based on the evolution of equal time interval data, the response relationships of valley settlement to the development of debris flow fans in the different terrains are analyzed. It is hoped that the study will assist in reasonable planning, site selection, population migration, and disaster prevention and reduction of debris flow events in areas susceptible to slope failure events.

## Study area

The upper reaches of Min River refer to the area in the upper reaches of Dujiangyan irrigation system and its tributaries, located at 30° 45'N–33° 10'N, 102° 35'E–103° 57'E (Fig. 1).

**Fig. 1** Location of the upper reaches of Min River, Sichuan Province, China



The study area is located in the northwest of the Sichuan basin, and represents a transition zone from the hilly area of the basin to the alpine canyon area on the eastern edge of the Qinghai Tibet Plateau. The topography of the area is complex, the differences of landforms are remarkable, and the river valleys in the region are deep and steep. Here, the current of the Min River is known to be swift. Faults in this area are relatively well developed, with neotectonic movements being noticeably strong. Proterozoic to Cenozoic strata are well exposed in this area. The Sichuan basin is transition zone from the land-sea monsoon region to the plateau monsoon region. Annual rainfall distribution is uneven, with obvious differences between the dry and rainy seasons. The mean annual temperature is 5.7 to 13.5 °C. River runoff is mainly the result of rainfall, with minor contributions from alpine snowmelt. Annual runoff is fairly stable, and inter-annual variability is small (Miao and Ding 2017). The formation of debris flow is closely related to local climate and environmental conditions. And a debris flow fan is the final product of the historic accumulation of debris flow (Fleischmann 1986). Under the combined effects of topography, geomorphology, tectonics, climate, and other factors, the morphological development and sedimentary characteristics of debris flow fans fluctuate, and then affect the distribution of valley settlements.

In the upper reaches of Min River, local residents consider the region to be divisible into four sub-regions, each with their own respective settlements. Thus, the region can be described as valley settlements, the half-hillside settlements (or two half-hillside settlements), the hillside settlements, and the high hillside settlements (Chen et al. 2007; Shen 2006). As the upper

reaches of the Min River valley are located relatively close to the river, a considerable portion of the land consists of cultivated terraces. In addition, highways are built along the valley, which is convenient for transportation. A large part of the settlements are distributed in the valley zone. Therefore, it is defined as “valley settlement.” The valley settlements themselves can be subdivided into accumulation fan settlements and river terrace settlements.

Figure 2 is an example of debris flow accumulation fan and valley settlement in the upper reaches of Min River.

## Materials and process

### Data sources

The data used in this study were obtained from two sources: (1) Institute of Remote Sensing and Digital Earth Chinese Academy (n.d.) (<http://ids.ceode.ac.cn/>) and (2) Geospatial Data Cloud (n.d.) (<http://www.giscloud.cn/>).

### Satellite image data of the upper reaches of the Min River

Through the Open Spatial Data Sharing Project, RAD1, from the Institute of Remote Sensing and Digital Earth Chinese Academy (n.d.) (<http://ids.ceode.ac.cn/>), free Landsat Thematic Mapper (TM, Landsat-5) images, Enhanced Thematic Mapper images (ETM, Landsat-7), and Operational Land Imager (OLI, Landsat-8) data were obtained. The image resolution for ETM and OLI is 30 m,





**Fig. 2** An example of debris flow accumulation fan and valley settlement in the upper reaches of Min River. **a** Anjiagou, village settlements and homestay settlement in country-level AAAA class scenic spot (Dayu Grange). **b** Cutougou, traditional Qiang village settlements-Qiangfeng Village

but both the ETM image and OLI image have a 15-m panchromatic band, which can be used for image fusion to improve the accuracy of visual interpretation. In this study, we obtained TM images from 1994, ETM images from 2004, and OLI images from 2014.

#### Digital Elevation Model (DEM) data of the upper reaches of Min River

DEM data for this study is derived from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) data, a model jointly developed by the Japanese Ministry of Economy, Trade, and Industry (METI) and NASA, and distributed free of charge to the public (<http://www.giscloud.cn/>). The spatial resolution of the data is 30 m, the data type is IMG, and the UTM/WGS 84 projection was adopted.

ASTER GDEM has released two versions of data, with the first version (V1) released in 2009, and the second version (V2) released in 2011. Due to cloud cover, boundary stacking caused by linear craters, uplift, dams, or other anomalies, data for the study region from the original

data of ASTER GDEM V1 are anomalous. The ASTER GDEM (V2) version uses an advanced algorithm to improve V1 of the GDEM images and increase the accuracy of data. METI and NASA have validated the accuracy of the V2 version of the GDEM data, and have shown that V2 effectively corrected the errors in the V1 data set.

#### Data processing

##### Preparations for different topographic data (elevations, slopes, and slope aspect) in the upper reaches of Min River

In order to analyze the response of valley settlements to the evolution of debris flow fans under different terrain conditions, elevation data, slope data, and slope aspect data were reclassified. The classification criteria of topographic factors used here are as follows:

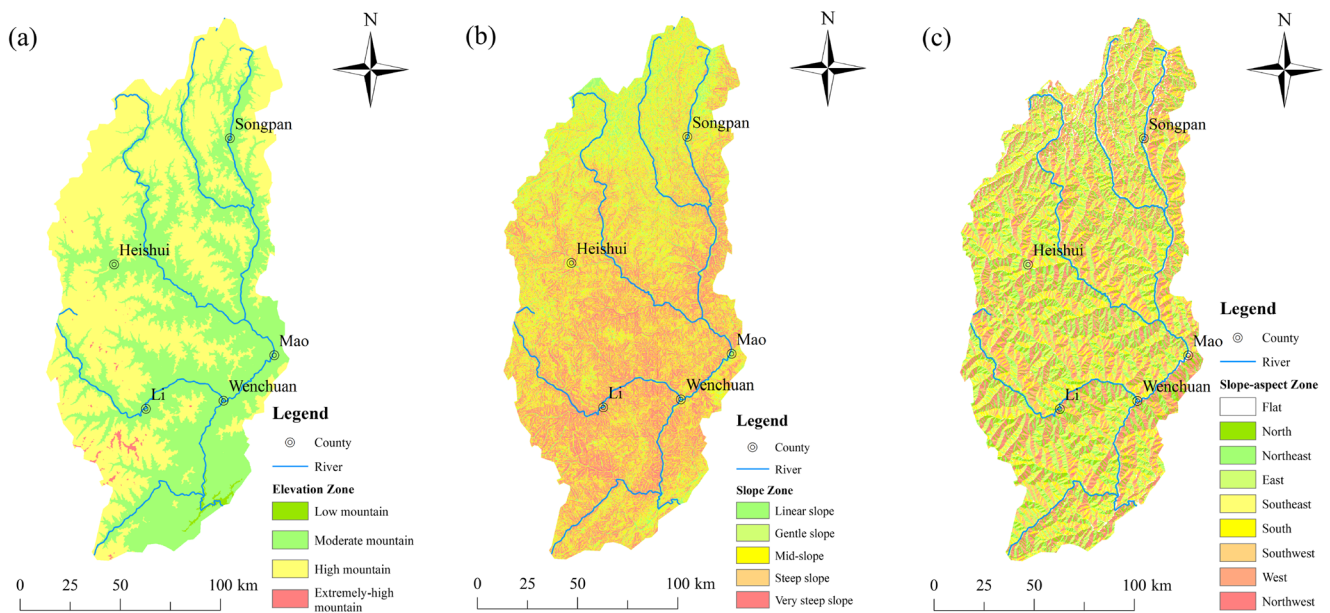
**Elevation classification:** Referring to the criterion of absolute height in the division of mountain types in China (Zhong and Liu 2014), the elevation of our study area is divided into four categories, namely, low mountain (800–1,000 m), moderate mountain (1,000–3,500 m), high mountain (3,500–5,000 m), and extremely high mountain (> 5,000 m) (Fig 3a).

**Slope classification:** According to the classification criteria for slope composition in a published hill slope survey, “Comprehensive control of soil and water conservation-General rules of planning for the national standard of the People’s Republic of China (n.d.) (GB/T15772-2008)”, the slope of the terrain in this study can be divided into five grades, namely, < 5° (linear slope), 5–15° (gentle slope), 15–25° (mid-slope), 25–35° (steep slope), and > 35° (very steep slope) (Fig 3b).

**Slope aspect classification:** The slopes in our study area can be divided into nine directional categories (Nan et al. 2015), namely, flat, north (0–22.5°, 337.5–360°), northeast (22.5–67.5°), east (67.5–112.5°), southeast (112.5–157.5°), south (157.5–202.5°), southwest (202.5–247.5°), west (247.5–292.5°), and northwest (292.5–337.5°) (Fig 3c).

##### Preparation of data on distribution of valley settlements and debris flow accumulation fans in the upper reaches of Min River

**Remote sensing data preprocessing:** In the process of acquiring ground objects and imaging, the influence of the satellite itself and the external environment act to distort the quality of the acquired images. In order to avoid the error caused by processing in the subsequent image application, it is necessary to preprocess the acquired original image data. This procedure includes image geometric correction, image fusion, image mosaics, and image cropping. This study employed the ENVI 5.1 software to preprocess the acquired images.



**Fig. 3** Different terrains in the upper reaches of Min River. **a** Elevation. **b** Slope. **c** Slope aspect

Information extraction for valley settlements and debris flow accumulation fans using multi-period remote sensing images: It is a complex process to study the evolution of valley settlements and debris flow fans in the upper reaches of Min River. Traditional on-site investigation and research often requires a great deal of manpower, as well as material and financial resources, and the resultant data do not have high integrity. Therefore, traditional research methods, combined with modern geographic information technology, are expected to produce a more comprehensive evaluation of the development of valley settlements and debris flow fans in our study area. Remote sensing images of the upper reaches of Min River are available for the years 1994, 2004, and 2014. Data from 2014 show the most recent boundaries of valley settlements and debris flow fans. Using Google Earth, interpretation of the remote sensing images in 2014 can delineate the valley settlements and debris flow fans in the region. In addition, field investigations were conducted to verify and correct the aberrations in satellite data. Based on field investigations, the distribution characteristics of valley settlements and debris flow fans were summarized. Under the ENVI 5.1 software platform, the characteristics of the valley settlements and debris flow fans are quantified as the limited condition of decision tree classification, and they are applied to the classification of remote sensing images obtained in 2014. Thirdly, compare the two results, comparison of field investigation results with conclusions from ENVI processing allowed for constant validation and revision of the description of settlements and debris flow fans. The method was then applied to the remote sensing image data from 1994 to 2004. Additional data on valley settlement areas and the geometric center points of the debris flow accumulation fans were also obtained by this analysis.

### Response analysis on valley settlements based on the evolution of debris flow fans under variable topographic conditions (elevations, slopes, and slope aspect)

Then data reflecting the position of valley settlements and debris flow fan geometric centers in 1994, 2004, and 2014 were superimposed on a terrain layer. The distribution and evolution of valley settlements and debris flow fans at different elevations, slopes, and slope aspect for three specific years bracketing two decades were determined, and the response relationships between them are discussed in the “Results and analysis” section.

## Results and analysis

### Distribution characteristics and evolution of valley settlements and debris flow fans in different terrains

As shown in Table 1, the elevation of the upper reaches of Min River falls mainly in the moderate mountain and high mountain categories, of which the area of moderate mountain elevation comprises 48% of the total, with the remaining 51% found in the high mountain region. Other terrains, including low mountains and extremely high mountains account for only 1%. Approximately 63 % of slope values range from 15–35°, equivalent to mid-slope and steep slope areas. Slope terrain area gradually increases from linear to steep slope, before decreasing in the very steep slope category. With a further increase of slope, the terrain area gradually decreases. The slope aspect was found to trend mainly east and southeast, with this area comprising 27% of the total. The extent of the

slope aspect area decreases from east > southeast > west > northwest > southwest > northeast > south > north > flat.

### Settlement distribution and debris fan concentration relative to elevation

By analyzing the distribution (number and density) of valley settlement areas (Table 2), we found that valley settlements are mainly located in the moderate and low mountain areas (< 3500 m), with the highest density concentration in the low mountain area. Settlement density in the moderate mountain area decreases then increases over time, whereas the high mountain area shows a continual reduction in density. However, the specific distribution patterns of valley settlements in 1994, 2004, and 2014 differ during each time period. In 1994, the number of valley settlement areas increased with the increasing elevation, while in 2004 and 2014, it increased first and then decreased with increased elevation. This indicates that in this area, the valley settlements gradually migrated to lower elevations. Following an in-depth analysis of each elevation, it was found that the evolution of valley settlements on differing elevation levels produced different patterns. In the low mountain area, the number and density of settlements in the valley increased with the time and then decreased, but the overall change was small and remained between 4 and 6% the highest value in 2004 moderate. The number and density of settlements in the moderate mountain region showed a similar pattern with time, increasing by 61% during the 1994–2004 time frame, followed by a sudden 288% increase from 2004 to 2014. In the high mountain area, the number and density of settlements decreased continuously over time, with an overall small change (13 to 38%) from 1994 to 2014 when compared with the moderate mountain data. No valley settlement distribution was recorded in the extremely high mountain area.

Based on the number of debris fans located during the three data collection years of 1994, 2004, and 2014 (Table 2), it is apparent that the incidence of debris flow fan formation has increased over the past 20 years, but the distribution pattern remains the same, in that debris fans are found primarily in the moderate mountain range (> 97%). The data also show that over the time range 1994–2004, the percentage of debris flow fans in the moderate mountain increased with a simultaneous decrease in the percentage of fans located in the low mountain areas. Interestingly, these trends are reversed in the data for 2014, in that percentage of debris flow fans occurring in the low and high mountain regions increased, with a concurrent decrease in percentage in the moderate mountain zone.

### Settlement distribution and debris fan concentration relative to slope

After considering the number of valley settlements in different slope regions (Table 3), it was found that the gentle slope area

was the most highly populated. During the time period 1994–2014, the number of settlements and settlement density showed a continued increase in each slope category, with the exception of linear slope. The number of settlements and settlement density in linear slope area decreased following a peak in 2004. This decrease was likely due to the effects of the May 2008 Wenchuan earthquake. In general, the gentle slope regions support the largest number of settlements. For both the gentle and mid-slope locales, a dramatic increase in the number of settlements occurred from 2004 to 2014. Therefore, the decrease of settlements in linear slope area reflected the gradual migration of peoples to the gentle, mid-, and steep slope areas. Following the May 2008 Wenchuan earthquake and post-seismic incidents, the number of valley settlements in the linear slope area was reduced to pre-1994 levels with settlements in other slope areas increasing to accommodate those displaced by landslides and flooding associated with the earthquake.

The distribution of geometric centers of debris flow fans for 1994, 2004, and 2014 are shown in Table 3. Overall, approximately one-third of the total number of geometric centers were found in the linear slope region. There is a noticeable increase in the frequency of debris flow activity from the period 1994–2004 to the period 2004–2014. In addition, the percentage of centers increased from 1994 to 2014 in both the linear and gentle slope regions, compared with decreases in center numbers for the mid-slope, steep slope, and very steep slope areas. During the period 1994–2004, the increase or decrease in the proportion of the geometric centers of the debris flow fans is relatively small, with an average change of 1 %, increasing to an average variation of 2 % in the period 2004–2014.

### Settlement distribution and debris fan concentration relative to slope aspect

By analyzing the distribution and density of valley settlements with regard to slope aspect for 1994, 2004, and 2014 (Table 4), it was found that the density of valley settlements were highest on the flat and northwest slopes in 1994 and 2004, switching to the flat and west slopes by 2014. During these 20 years, the distribution of areas shifted axisymmetrically, from north, east, west, and northwest in 1994–2004 to southeast, south, southwest, and west in 2004–2014. Following in-depth analysis of each slope aspect, an evolution model of the valley settlements can be constructed for three segments. The first segment is comprised of the flat, southeast, south, southwest, and west slope directions. During the years 1994–2004, the number and density of settlements in this segment showed a gradual increase between 24 and 88%; however, in the following decade, the number and density of settlements spiked, increasing by 125–2423% 1994 values. The northeast and east



**Table 1** Statistics of the different topographies in the upper reaches of Min River

Elevation		Slope		Slope aspect	
Classification	Area/km <sup>2</sup>	Classification	Area/km <sup>2</sup>	Classification	Area/km <sup>2</sup>
Low mountain	76.06	Linear slope	1358.37	Flat	575.25
Moderate mountain	10,868.58	Gentle slope	2776.42	North	2328.97
High mountain	11,400.24	Mid-slope	6418.8	Northeast	2615.39
Extremely high mountain	82.63	Steep slope	7708.2	East	3068.88
		Very steep slope	4165.72	Southeast	3039.74
				South	2470.56
				Southwest	2659.67
				West	2846.36
				Northwest	2822.69

slope aspects are the components of the second segment. Here, the number and density of settlements increased gradually, with an overall increase of 1994 values by 15 to 67%. A decadal breakdown indicates the increases in the second segment were 3 to 9% in 1994–2004, and 11 to 54% in 2004–2014. The third segment, represented by the northwest and north slope directions, contrasts with the first two segments in that during the decade of 1994–2004 an increase of density between 2 and 3% did occur, however, during the period 2004–2014. The number and density of settlements decreased between 40 and 54% 1994 levels.

Based on the distribution of geometric centers of debris flow fan in relation to slope aspect in 1994, 2004, and 2014 (Table 4), it is found that the geometric centers of debris flow fans in the upper reaches of Min River are concentrated in the flat land and northwest, similar to the density of valley settlements during the period 1994–2004. During the past 20 years, the number of geometric centers of the debris fans has followed an overall increasing trend of increase, but the spatial distribution pattern has not changed significantly. By analyzing the changes of geometric centers on each slope aspect, four conclusions can be drawn. First, the

percentage of geometric centers increases in the flat region over time. Second, percentages of geometric centers in the north, southeast, south, and west decrease in number during the first decade, but increase during the second decade. Conversely, the third conclusion describes an increase followed by a decrease in the percentage of geometric centers over time for the east and southwest slopes. Finally, both the northwest and northeast slopes show steady decreases in the percentage of geometric centers over time.

### Response analysis of valley settlements to the evolution of debris flow fans under different topographic conditions

In order to fully consider the response of valley settlements to the evolution of debris flow fans, focus must be placed on the response of settlements built following previous debris flow emplacement, on what can be considered accumulation fans. An accumulation fan in this context is analogous to an alluvial fan that receives periodic sediment input following erosion events. Here sediment input is the result of slope failure. If surface data of debris flow fans are superimposed on the

**Table 2** Distribution of valley settlements and debris flow fans versus elevation zones in 1994, 2004, and 2014

Distribution	Year	Elevation zone			
		Low mountain	Moderate mountain	High mountain	Extremely high mountain
Number of valley settlements patches / number (density of valley settlements patches/(number/km <sup>2</sup> ))	1994	651 (8.56)	2549 (0.23)	2779 (0.24)	0 (0)
	2004	679 (8.93)	4116 (0.38)	2421 (0.21)	0 (0)
	2014	641 (8.43)	15,970 (1.47)	1508 (0.13)	0 (0)
Number of debris flow fan geometric centers / number (percentage of debris flow fan geometric centers/%)	1994	5 (2)	219 (97)	1 (1)	0 (0)
	2004	4 (1)	241 (98)	1 (1)	0 (0)
	2014	7 (2)	310 (97)	2 (1)	0 (0)

**Table 3** Distribution of valley settlements and debris flow fans versus slope zones in 1994, 2004, and 2014

Distribution	Year	Slope zone				
		Linear slope	Gentle slope	Mid-slope	Steep slope	Very steep slope
Number of valley settlements patches/number (density of valley settlements patches/(number/km <sup>2</sup> ))	1994	871 (0.64)	2869 (1.03)	870 (0.14)	711 (0.09)	658 (0.16)
	2004	1100 (0.81)	3290 (1.19)	1223 (0.19)	936 (0.12)	667 (0.16)
	2014	789 (0.58)	10,304 (3.71)	4459 (0.69)	1876 (0.24)	691 (0.17)
Number of debris flow fan geometric centers/number (percentage of debris flow fan geometric centers/%)	1994	68 (30)	35 (15)	58 (26)	40 (18)	24 (11)
	2004	75 (31)	44 (18)	59 (24)	43 (17)	25 (10)
	2014	98 (31)	71 (22)	69 (22)	54 (17)	27 (8)

location of valley settlements (Table 5), it is found that the accumulation fan settlements increased with the increase of debris flow activities during period 1994–2014. In some instances, more than one settlement has been constructed on an accumulation fan, thus in order to facilitate analysis, data for settlements on a number of accumulation fans were merged in this study.

#### Response analysis of valley settlements to the evolution of debris flow fans at different elevation

The distribution of valley settlements and debris flow fans in the upper reaches of Min River is related to the elevation, and varies with a common dependent variable, elevation. Statistically, the distribution between the two is similar, indicating that there is a mutual response between them. In fact, there is a linear relationship between valley settlement density distribution and the density of debris flow fans, relative to elevation. Through the comparison of the respective fitting relations of data from the 3 years in which records were collected, the coupled relationship between valley settlements and debris flow accumulation fans can be shown to change with time. During the time frame 1994–2014, the rate of change of valley settlements along with debris flow fans increased, then decreased (Fig. 4).

#### Response analysis of valley settlements to the evolution of debris flow fans under varying slope conditions

A regression analysis between valley settlement density and geometric center density of debris flow fan shows that they conform to a two polynomial function model on the slope distribution, that is, the density of valley settlements increases first and then decreases with the increase of geometric center density of debris flow fans (Fig. 5). From 1994 to 2014, the vertex (maximum) of the coupling curve of valley settlement and debris flow fans, relative to slope, increases with time. Moreover, the symmetrical axis of the curve moves in a gradual

direction toward increasing accumulated fan density. These relationships show that the difference between the coupling relationship between valley settlements and debris flow fans is becoming larger and larger, and also indicates that the distribution of river valley settlements and debris flow fans on various slopes is moving to a certain gradient area.

#### Response analysis of valley settlements on the evolution of debris flow fans for differing slope aspect

The relationship between the density of valley settlements and the geometric center density of debris flow fans in regard to the slope aspect is found to conform to a linear model, namely, with increasing geometric center density of debris flow fans, the density of the valley settlements also increases (the coupled mathematical expressions are linearly increasing functions; Fig. 6). By comparing the three time coupling curves and mathematical expressions, it can be seen that the linear slope of the coupling relation increases with time ( $k_{2014} > k_{2004} > k_{1994}$ ), that is, the density of valley settlements increases with the increase of the rate of change of geometric center density of debris flow fans over time. It shows that the change of valley settlements on slope aspect over time will be more and more obvious when combined with the influence of debris flow accumulation fans.

## Conclusions

In the upper reaches of Min River, the natural environment is very special, the geological structure is complex, and the disturbance of human activities to the mountain ecological environment is frequent, which creates a fragile, disaster-prone ecological environment in the upper reaches of the Yangtze River. This study considers the relationship between debris flow fan evolution and valley settlements. Discussion of the distribution characteristics debris flow fans and valley settlements under different terrain conditions, and comparing and analyzing the influence and function of each have important



**Table 4** Distribution of valley settlements and debris flow fans versus slope aspect zones in 1994, 2004, and 2014

Type	Year	Slope aspect zone								
		Flat	North	Northeast	East	Southeast	South	Southwest	West	Northwest
Number of valley settlements patches/number (density of valley settlements patches/number/km <sup>2</sup> )	1994	527 (0.92)	841 (0.36)	510 (0.20)	785 (0.26)	186 (0.06)	82 (0.03)	406 (0.15)	1083 (0.38)	1559 (0.55)
	2004	990 (1.72)	866 (0.37)	556 (0.21)	812 (0.26)	304 (0.10)	103 (0.04)	650 (0.24)	1339 (0.47)	1596 (0.57)
	2014	2223 (3.86)	517 (0.22)	854 (0.33)	899 (0.29)	1522 (0.50)	2599 (1.05)	3053 (1.15)	5753 (2.02)	739 (0.26)
Number of debris flow fan geometric centers/number (percentage of debris flow fan geometric centers/%)	1994	41 (18)	41 (18)	31 (14)	6 (3)	3 (1)	5 (2)	12 (6)	29 (13)	57 (25)
	2004	47 (19)	40 (16)	33 (14)	12 (5)	3 (1)	4 (2)	18 (7)	27 (11)	62 (25)
	2014	67 (21)	54 (17)	40 (12)	13 (4)	7 (2)	9 (3)	19 (6)	38 (12)	72 (23)

**Table 5** Statistics of accumulation fan settlements

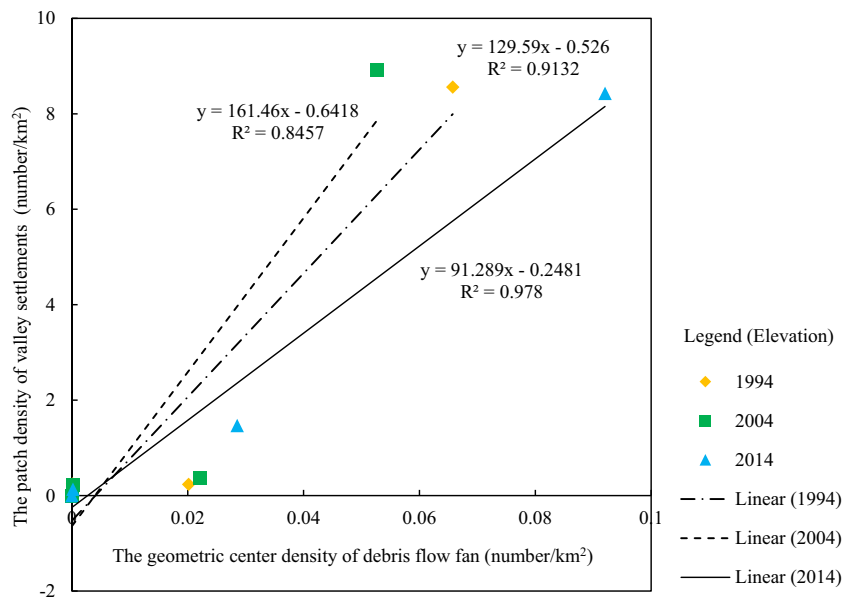
Year	1994	2004	2014
Number of accumulation fan settlement	109	134	169
Number of accumulated fans in a settlement	74	108	145

theoretical significance and reference value for clarifying the reasonable planning, site selection, population migration, and debris flow disaster prevention and reduction in areas prone to slope failure.

The main conclusions of this study are as follows:

- (1). The distribution of valley settlements and debris flow fans varies with time under different topographic conditions. Valley settlements of high density are concentrated in low mountain areas and show clustering in the moderate mountain areas. Debris flow fans are rarely distributed in low mountain and high mountain regions, and are primarily concentrated in the highly populated moderate elevation mountains. In regard to the influence of slope, the valley settlements gradually shifted to low slope zones during the 1994–2004 decade. In contrast, the valley settlements moved from lower and higher elevations to areas with slopes of 5–35° from 2004 to 2014. Debris accumulation fans are mainly concentrated on slopes below 35°. Considering slope aspect, the distribution of valley settlements basically migrated from north, east, west, and northwest facing slopes from 1994 to 2004, to the southeast, south, southwest, and west facing slopes during 2004–2014. Debris flow fans show an increasing trend in occurrence, but the spatial distribution pattern did not change significantly.
- (2). The response of valley settlements to the evolution of debris flow fans under different topographic conditions in the upper reaches of Min River is remarkable. In regard to elevation, the distribution of both parameters has an increasing linear relationship, and the coupling relation of the two changes with time. Specifically, the rate of change of valley settlement with the debris flow fan events first increases and then decreases. Considering the relationship of debris flow fans and valley settlements with slope, both conform to the two polynomial function model, that is, the density of valley settlements increases first and then decreases with the increase of the geometric center density of the debris accumulation fans. For slope aspect, the relationship with valley settlement density conforms to a linear model, and the variation rate of the valley settlements density with the geometric center density of debris flow increases as time goes on ( $k_{2014} > k_{2004} > k_{1994}$ ). In addition, the change of valley settlement distribution over long periods of time will be more and more obvious when

**Fig. 4** Response relationship between the patch density of valley settlements and the geometric center density of debris flow fans on elevation

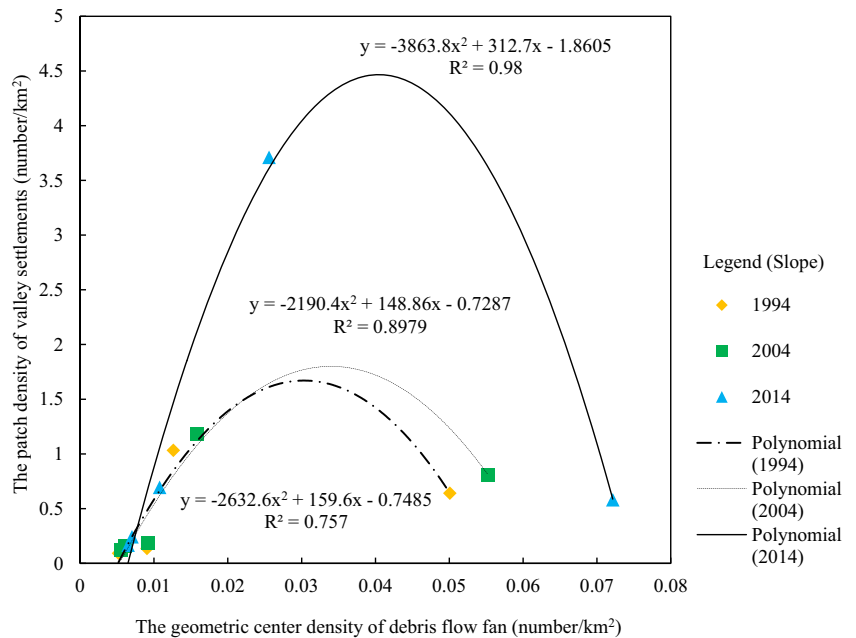


combined with the influence of debris flow fans under different topographic conditions.

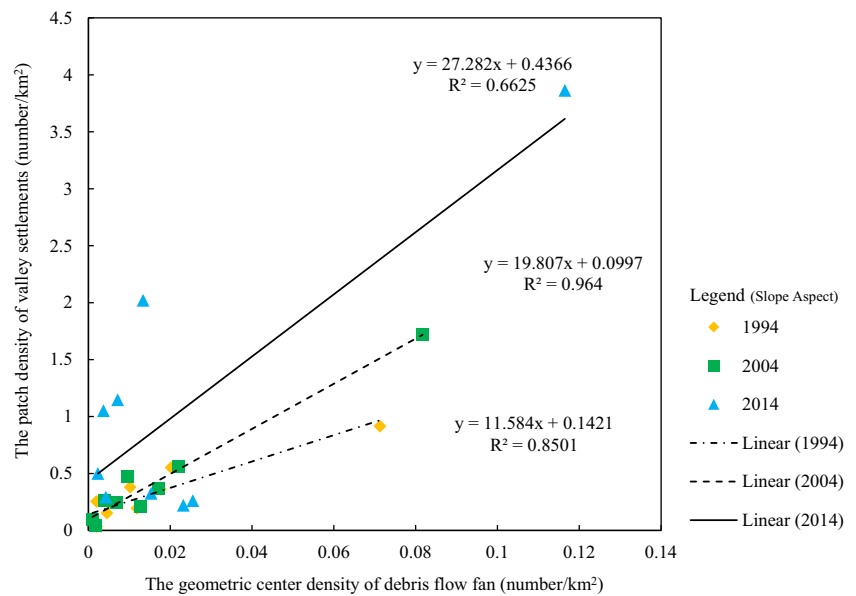
Due to the limitation of some parameters, there is no precise expression for the response of valley settlements to the evolution of debris flow fans in a long time series. Also, the economic impact of the debris flow fan events on valley settlements and the physical characteristics of debris flow fans require further analysis. These inadequacies affect the integrity of the present research results to a certain extent, and as such the research results are not convincing enough to provide

a theoretical basis and practical guidance for the development of valley settlements and the prevention and control of debris flow disasters. In future research, we will continue to focus on the evolutionary processes of valley settlement and debris flow accumulation in this basin, and actively complement the response research content presented here on valley settlement to the evolution of debris flow fans. At the same time, the scale of the study will be refined by selection of a specific debris flow gully with valley settlement for study, and the relationship between valley settlement and debris flow accumulation fan will be addressed accordingly.

**Fig. 5** Response relationship between the patch density of valley settlements and the geometric center density of debris flow fans on slope



**Fig. 6** Response relationship between the patch density of valley settlements and the geometric center density of debris flow fans on slope aspect



**Funding information** The study was financially supported by the National key research and development program (Grant No. 2018YFC1505402), National Natural Science Foundation of China (Grant No. 41871174), Opening fund of State Key Laboratory of Geohazard Prevention and Geoenvironment Protection (Chengdu University of Technology) (Grant No. SKLGP2019K018), and the Fundamental Research Funds for the Central Universities (Grant No. 2682019CX19).

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