SPECIAL ISSUE

Characteristics of spatial distribution of debris flow and the effect of their sediment yield in main downstream of Jinsha River, China

Hongjiang Liu · Hengxing Lan · Yi Liu · Yue Zhou

Abstract Debris flow hazard posts a big threat to the main downstream of Jinsha River where a number of huge power stations are under construction. The characteristics of spatial distribution of debris flows and the effect of their sediment yield on the reservoir areas have been studied. An automatic recognition module was developed to extract the geometry of debris flow channels from remote sensing data. Spatial distribution pattern of debris flows is obtained through combining the inventory database and multi-source remote sensing investigation. The distribution of debris flows has high dependency on the various factors including geology, geomorphology, climate, hydrology and human economic activities. The debris flows distributed in the study area are characterized by group and pair distribution, uncompleted deposition fans, highly controlled by faults and tectonic activities, spatial variation between left bank and right bank, and different subdivisions. The sediment yield caused by debris flow activates is evaluated using multi-year observation data from numerous observation stations. Quantitative studies have been performed on the relationship between the sediment yield and the debris flow area. A relatively fix ratio of 2.6 ($\times 10^4$ t/km^2) has been found in different subdivisions of main downstream area which shows that the source of sediment discharged into Jinsha River primarily come from debris flow activities. Another ratio is evaluated to represent the transforming possibility of debris flow materials to bed-sediment load and suspended-sediment load in the river. Based on these findings, the potential effect of sediment yield caused by debris flows on reservoir areas is discussed. The zonation map shows the different effect of debris flow sediment on different dam site area which shows a good agreement with variation of debris flow spatial distribution.

Keywords Jinsha River · Debris flow · Spatial distribution · Sediment yield · Hydropower dam · Remote sensing

Introduction

The lower reaches of Jinsha River have attracted extensive attentions nationally and internationally due to their abundant resources for water and electricity. According to the China's State Power Planning, four large-scale cascade hydropower stations will be built along the lower reaches of Jinsha River, i.e., Xiangjiaba, Xiluodu, Baihetan, and Wudongde. All these four stations will have huge installed capacity with magnitude of 10^6 kW. However, debris flows are becoming very active due to comprehensive effects of the topography, geology, climate, and human activities in this special geographical location. As a result, they pose the major threat to the construction of these huge cascaded hydropower stations. Debris flows will threaten the life of hydropower station and affect its normal operation by transporting sediment to the downstream and depositing in channels through the dam sites. In addition, it will cause a large number of casualties, damage to roads, building, mines, and farmland.

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Many researches have been carried out in the area of debris flow disasters, mainly focusing on the theoretical research, laboratory test and simulation, field survey, hazard assessment, and engineering protection (Takahashi 1991; Tang and Zhang 1992; Du 1993,1996; Wu et al. 1997). Numerous activities have been conducted by ministry of Chinese Railway, Water Conservancy, Transportation, Urban Construction and Mining related research, design and construction for debris flow prevention and mitigation (China Institute of Water and Soil Conservation 1993). However, due to the high mountainous topography, deep valleys, inconvenience of the traffic in the lower reaches of Jinsha River, systematic investigations on their debris flow gullies were limited in some part of the key areas. In the 1980s, Chengdu Institute of Mountain Hazards and Environment, Chinese Academy of Sciences began the regional inventory survey of debris flow and landslide which was restricted in the areas along the road at that time. Some of the corresponding outputs can be found in the book of "Debris Flows along Chengdu-Kunming Railway" (Zhong 1996), the report of "debris flows and landslides in the area of Sichuan Province along the downstream of Jinsha River" (Zhong and Liu 1991). Remote sensing method was used in this region. For example, about 438 debris flow gullies and more than 400 landslides with magnitude greater than 1×10^6 m³ along the lower reaches of the Jinsha River had been identified by means of the interpretation of aerial photographs, most of which are still active (Wang 1999). However, these researches have not made summary on the scientific evaluation for the regional rule of debris flows spatial distribution. The spatial distribution law of debris flow in lower reach of the Jinsha River is difficult to carry out due to the complexity of debris flow mechanism and relatively inadequate information in both spatial and temporal. Hence, the characteristics of spatial distribution of debris flow in this region are still not well understood.

Debris flows initiate in the forms of high intensive soil erosion. The study on the process of channel erosion and sediment yield of debris flow is not sufficient due to the complexity of the mechanism of erosion and sediment yield for debris flow. Few researches have been conducted on the quantitative evaluation of channel sediment yield. A few of researches have been carried out on regional debris flow erosion and sediment yield in the lower reaches in the Jinsha River. Cui et al. (2000) showed that the strong activities of debris flow in the lower reach of Jinsha River provide 40% of the sediment yield of the Yichang hydrological station with an area of only 9.27% of the upper reach of Yangtze River. Sediment yield has relationship with ground characteristics, such as topography, geology, lithology, vegetation, cultivated land, economic development, etc. Rainfall and river run-off are the two major influence factors to river sediment yield (Liu and Zhang 1991, 1995; Liu 1997). Lu (1989) showed that lithology controls the sediment yield. In this area, high intensity sediment yield induced by debris flow causes special channel characteristics in both plan and profile (You and Chen 2003). The sediment center is located along the Xiaojiang Fault, especially in Qiaojia–Ningnan–Jinyang. Most of the sediment comes from gravity erosion (Jia 2007). Sediment yield is closely correlated to rainfall (Deng 1997; Pan 1999). Erosion modulus had been analyzed through sediment observation data. Ratio of sediment delivery (RSD) in upper reach of Yangtze River ranges from 0.23 to 0.27 (Yu et al. 1991; Chen and Liu 2000). And debris flow sediment yield in different areas should have their own specific modulus and parameters (Chen and Zhu 2000).

Most of the research works have concentrated focus more in the field of slope erosion and sediment yield. However, Channel erosion is more critical than slope erosion during the debris flow process in the study area. The product of channel erosion and sediment yield usually constitutes the major part of a basin. Bartley et al. (2007) used methods of erosion pins, erosion trough, cross-section observation to study and estimate the total sediment yield in a semi-arid grazing land by categorizing it as slope, channel and the main stream sediment yield. Results show that channel sediment yield is much larger than the slope sediment yield. Sediment yield mainly comes from the ditch material deposition, and sources of supply of material are gradually decreasing.

To sum up, the studies on the spatial characteristics of debris flow activities are limited due to the low availability of critical data. Few researches have been conducted on the debris flow channel erosion and sediment yield while many on the slope erosion and sediment yield. Therefore, it is necessary to carry out systematic investigation about debris flow hazard in this area, and to summarize its spatial distribution rule, to evaluate and analyze the effects of sediment yield from channelized debris flows.

This paper will concern four questions for main downstream of Jinsha River: What are the spatial distribution characteristics of debris flows? What is the relationship between debris flow distribution and sediment yield? How materials of debris flow activity have been transformed to suspended sediment and what is its effect on the sediment in Reservoir areas? How will sediment yield from debris flow affect the operation of huge-scale cascaded hydropower stations? The studies carried out to answer these questions have great significance of functional guidance to the effective prevention and mitigation of debris flow hazard. They will also provide scientific guidance to the river sediment control, watershed development and

utilization of hydropower and eco-environmental impact assessment.

Study area

Jinsha River is the upper reach of the Yangtze River (Fig. 1). It originates from the peak of east Geladan Snowy Mountain (6,621 m in elevation) in the Tanggula Mountains. It begins at Tongtian River junction in Yushu County in Qinghai Province, and end at Yibin City in Sichuan Province, with a total length of 2,326 km. It flows through three provinces: Tibet, Yunnan and Sichuan. It can be divided into three sections, i.e., upper, middle, and lower. Upper section begins from Yushu County to the town of Shigu with a length of 994 km and a water head fall of 1,722 m; the middle section is from Shigu town to Panzhihua City with a length of 564 km and a water head fall

of 838 m; lower section end at Yibin city, with a length of 733.4 km and a water head fall of 719 m. Jinsha River valley crosses the rugged mountain cliffs and becomes the geographic natural boundary of provinces of Sichuan, Yunnan, and Tibet. In the ancient time, Jinsha River was also known as Flooding river, Rope river as in Book of "Yugong", Black river as in the Book of "Mountains and Seas", Lu River, Mahu River, Lishui, Lijiang, or God River.

The lower reaches of Jinsha River have been selected as an ideal place for exploiting and constructing large hydropower projects since it is characterized by narrow gap between sections, deep valley, relatively small population, and the low-cost relocation. Since the late twentieth century, a national plan of western development strategy has been made for developing the west electricity recourses and transporting them to the East. Before 2020, 14 large-scale hydropower stations will be constructed along the

Fig. 1 Comprehensive map of the study area
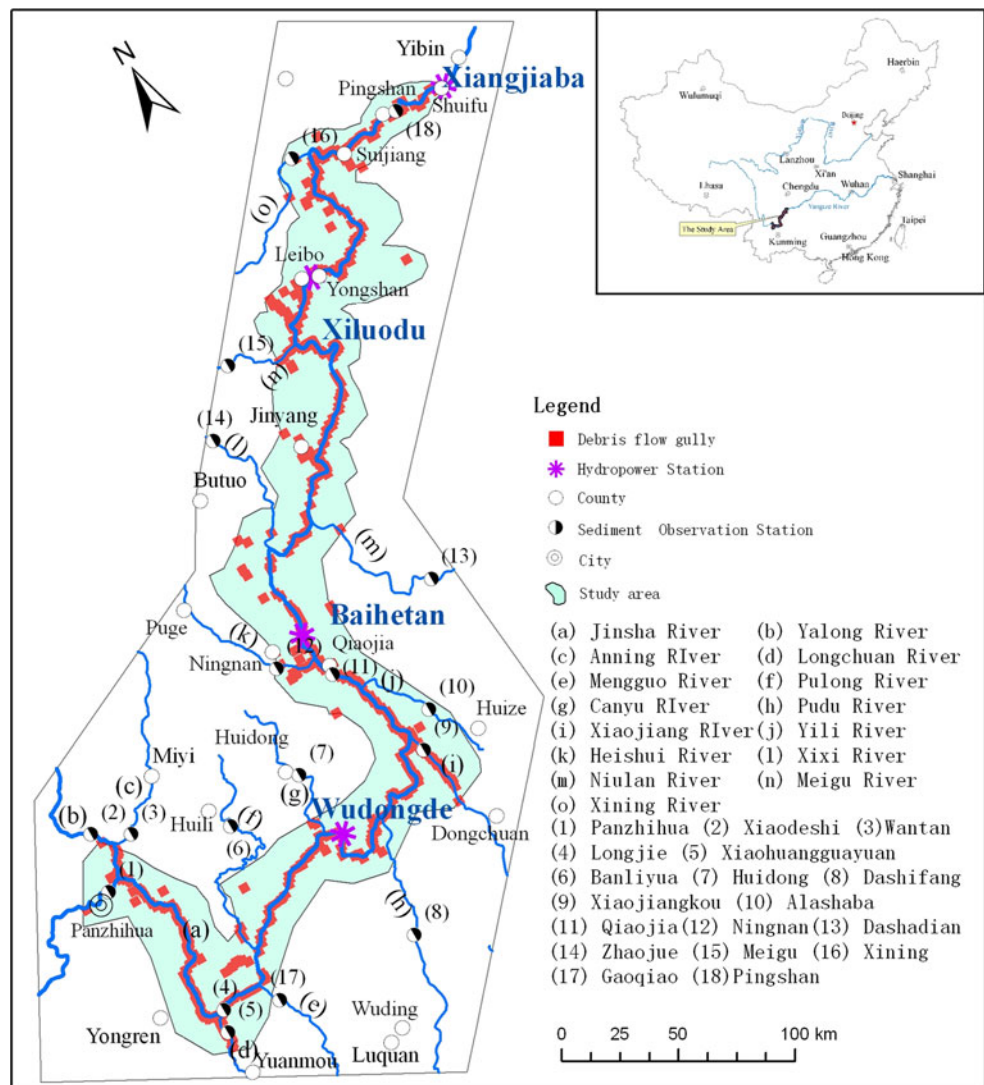
Jinsha River. Four of them are located in downstream with total capacity of 3.85×10^7 kW and ten located in upper and middle reach with total capacity of 2.074×10^7 kW. Four large hydropower stations, namely Xiangjiaba (installed capacity of 6.00×10^6 kW), Xiluodu (capacity 1.26×10^6 kW), Baihetan (installed capacity of 1.25×10^6 kw) and Wudongde (installed capacity of 7.40×10^6 kw), are located in the study area, which double more than capacity of the Three Gorges.

The lower reaches of Jinsha River are located in the transition zone between first and second topographic step and the transition zone of Hengduan Mountains and the eastern edge of Qinghai-Tibet Plateau, Yunnan-Guizhou Plateau and the Sichuan Basin where Indian Ocean plate is subducting beneath the Eurasian plate. They are characterized by very complex geological structure, strong mountain surface processes, strong crustal movements, frequent seismic activities, steep terrain, fragile rock mass, shallow soil, and vulnerable eco-environment. In addition, meteorological record shows high annual precipitation (1,000 mm in average) which is monsoon type and heavy terrain rainstorm. These factors contribute the strong activity of debris flows and their extensive distribution.

The outcrop in study area is dominated by the Jurassic Shaximiao group with an area of 639.4 km². The primary lithologies are sandstone and mudstone which nearly cover 50% of the study area. Affected by the tectonic activities, the controlling structures orient from nearly south to north. The water system shows a similar pattern. Three main fault zones distribute in the area, the Luzhijiang fault, the Xiaojiang fault and the Ebian-Jinyang fault. The Xiaojiang fault zone is a deep and active fault zone with length of more than 400 km. It is composed of several sub-faults with a very complicated internal structure induced by multi-phase tectonic activities. Debris gullies were intensively developed along the fault zones (Lan et al. 2004), threatening the Baiheran hydropower stations. Wudongde reservoir area is affected by Luzhihijiang fault zone and Xiluodu reservoir area by Ebian-Jinyang fault zone.

The National standard of Earthquake Dynamic Parameter in China GB18306-2001 (2001) suggests that the study area is located in the region where the value of peak ground acceleration (PGA) is greater than 0.15 g which means seismic intensity is greater than VII (Table 1). The seismic intensity in some areas is up to IX. Two earthquake centers are located in study area: one is situated along Ningnan–

Qiaojia–Dongchuan, with a PGA value of 0.25–0.30 g or seismic intensity of VIII; the other is located near Yongshan–Leibo with a PGA value of 0.20 g and corresponding seismic intensity level of VIII. The probability for debris flows outburst is very high in the region where the seismic intensity is greater than VII.

Rapidly uplifting and violently downward cutting make the river valley into V-shape with elevation difference from 1,000 to 3,000 m where the hillslopes are steeper than 30°–50°. Landsliding and debris flows are more prone to occur along these instable slopes.

The climate in the study area mainly belongs to hot and dry valley-river-type. From east to west, it follows climate zones which are transiting from the humid, sub-humid and semi-arid to dry-hot valley gradually. Debris flows were well developed with almost all kind of the climate types. Rainfall is strongly influenced by both terrain types and seasons. In winter, it is controlled by the air stream in South Branch of Tibet Plateau while in summer by both southwest and south east monsoon from Pacific Ocean. It shows a clearly dry-wet season type with 90% of precipitation occurring in wet season from May to October. Annual precipitation decreases gradually from east to west. Based on the data from the precipitation stations (Table 2), the annual precipitation increases gradually along the Jinsha River and the largest amount of rainfall is located at Pinshan Station which is the lower reaches of the area.

The population in the study area has been increasing rapidly since the Ming and Qing Dynasties more than 500 years ago (Fig. 2). As the growth of population and the increase of human socio-economic activity, ecological environment deteriorates continuously which intensifies the debris flow hazard.

Generally, debris flow occurs widely in the study area due to the strong monsoon climate, fragile eco-environment, and high pressure from population. In addition, the unreasonable human activities such as overgrazing, deforestation and reclamation aggravate the debris flow and other mountain hazards. Since the late 1980s, construction of infrastructure in lower reaches of Jinsha River grows dramatically. These large-scale projects and the ever-increasing human activities in the area make ecological environment more fragile which results in more frequent and severer debris flow activities.

Methods

Two major approaches are used: (1) integration of multi-source and multi-temporal remote sensing technology for characterizing the spatial distribution of debris flows, (2) quantitative modeling for estimating sediment yield from debris flows based on multi-years observation data.

Table 1 Comparison between earthquake dynamic acceleration and seismic intensity

PGA	<0.05	0.05	0.1	0.15	0.20	0.30	≥0.4
Intensity	<VI	VI	VII	VII	VIII	VIII	≥IX

Table 2 Precipitation stations and their average monthly precipitation in the Jinsha River downstream area (mm)

| Stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Dec	Nov	Mean
Sanleizi	3.3	2.6	3.2	12.6	34.0	159.3	196.2	164.4	120.8	52.5	11.8	6.0	766.4
Longjie	3.2	2.6	3.2	10.5	41.0	118.6	140.4	135.4	94.1	51.1	14.2	5.3	619.5
Jiangyi	4.5	3.6	6.8	14.6	67.4	158.5	181.6	191.6	140.2	79.0	15.4	18.0	881.3
Tongan	6.0	4.8	8.4	19.8	64.1	200.9	225.2	196.2	132.7	70.5	20.4	10.5	959.2
Shangtang	13.4	16.0	17.6	41.0	115.2	200.0	197.1	146.1	114.2	78.9	30.1	8.6	978.2
Tianba	6.4	8.3	8.2	17.7	52.4	118.0	132.1	96.9	72.7	48.5	18.0	5.4	582.1
Qiaojia	9.7	9.3	11.0	21.3	80.3	181.8	138.4	108.0	108.5	78.1	21.9	6.8	775.0
Hongzhuanping	5.5	3.4	8.4	20.8	73.5	157.5	132.0	112.5	117.3	33.0	16.4	3.0	683.2
Huapingzi	4.2	3.5	10.5	31.7	71.3	122.7	127.8	108.1	84.8	39.4	14.9	3.4	622.2
Pingyuan	18.3	21.1	15.5	56.0	103.0	158.4	210.9	205.4	159.6	61.3	38.8	9.2	1,032.3
Mahu	18.5	21.4	32.0	64.5	107.4	145.7	193.1	248.4	137.9	79.9	35.5	19.5	1,103.9
Xinhua	9.9	12.8	26.2	56.6	97.3	127.1	192.8	223.9	104.8	54.1	24.1	10.4	939.9
Pinshan	9.1	15.1	25.3	56.6	82.5	139.6	213.6	244.4	95.9	54.3	23.8	9.5	969.7
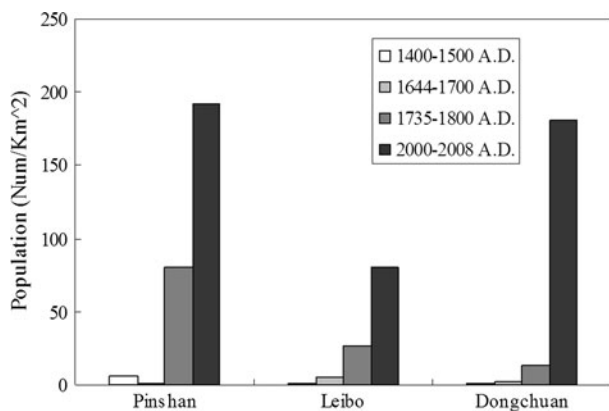
Fig. 2 Population density growth in the study area during the period from 1,400 to 2,008 (n/km^2)

Spatial distribution of debris flows

Remote sensing technology has a broad application in the geohazard studies. The integration of multi-angle, high-spectral and radar provides important data source for the remote debris flow distributed areas where traffic is not convenient.

Combining regional background environmental conditions such as geomorphic feature, vegetation, land cover, soil types extracted from remote sensing data with the 1:500,000 geological map, the landmark of the debris flow active area can roughly be divided into three types: rock and bare soil, vegetation and grassland. Rock in the study area is mainly feldspar quartz sandstone with interbedded mudstone. Typical debris flow channel is usually composed of initiation area, transportation area and deposition area (Lan et al. 2008). The initiation area often accompany with large-scale collapse or landslide. As a result of intensive tectonic evolution, joints were well developed in rock

mass. Rocks and soils are easily detached from slope and turn into loose materials which become the source for debris flows. This area usually contains some water but no tall trees grow on it. In the transportation area, more bare lands are exposed in the channel which is induced by the shearing movement of debris flow materials. A large amount of sediments accumulate in the deposition fans. They are often abundant in water and notorious and good for agriculture land. The high moisture capacity of materials and damaged vegetation cover can be identified from remote sensing images for the recognition of debris flows.

An automatic identification model was developed to extract the debris flow information from spectral database. According to spectral characteristics of reflection from grassland, shrub, and quartz sandstone (Fig. 3), bands 5 4 2 are selected. The spectrum curves have an absorption peak for shrubs and a reflection peak for grass for band 5 whose wavelength is nearly 1.5 μm. The spectrum curve for rock is relatively flat. Loose debris flows fans generally contain a certain amount of water. 2 and 4 bands are sensitive to water. Therefore, the use of bands 5 4 2 of remote sensing images is able to extract debris flow channels.

Soil moisture can be described by humidity index and vegetation cover by Green index. Both indices can be calculated from the spectrum characteristics of images through which debris flow channels can be extracted automatically. The image pixels in deposition area have higher humidity index and lower green index than those in other areas. Difference analysis between the images at various phases can effectively improve the recognition of debris flow channel and reduce ambiguities.

A density slice method is used to characterize debris flow gullies from the enhanced images. By checking and verifying the pixel values, it can be determined that the best density slicing value for ETM image is 34–78, and TM
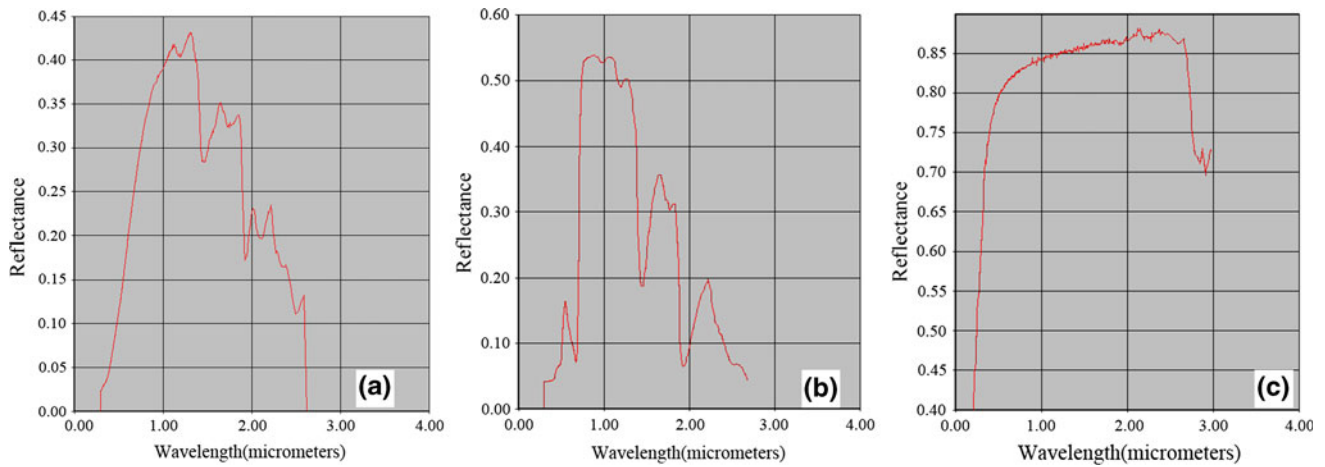
Fig. 3 Some typical landmark spectrum in debris flow activity area (USGS and JPL). a Spectrum of grassland, b shrub, and c Rock

15–30. A masking technology is then used in ENVI software to extract the geometry of debris flow channels at certain phase. Figure 4 shows the debris flow recognition process near Xiaojiang River in the study area. The green and humidity index are calculated based on the raw ETM image. The enhanced difference between green index and humidity index is shown in image (b). Image (c) shows final debris flow channel distribution. It is found from images (a) and (c) that both of the valley-type and slope-type debris flow are extracted well. Its accuracy is greater than 85% with verification of field survey.

Estimating debris flow channel sediment yield

The channel sediment yield research has drawn more attentions. Difficulties exist due to the data accuracy and availability of observational data. In the study area, multi-years observation data are available at a great number of stations in the downstream of Jinsha River. Table 3 shows the annual sediment observed in major stations for nearly 30 years.

Sediment yield effect of debris flow is analyzed through the multi-year hydrological sediment observation data at

Panzhihua, Longjie, Qiaojia, and Ping Shan. Figure 5 shows the 30 years trend of sediment discharged into Jinsha River at Qiaojia observation station. The amount of sediment yield is calculated by averaging the sediment discharge of each control station and the proportion of bed load and suspended load. The sediment from major tributary rivers is deducted to obtain the final sediment yield by debris flow. The characteristics of sediment transportation at the major control stations are shown as follows (Table 3).

Slope erosion and sediment yield were often simulated using the USLE Model (Universal Soil Loss Equation), which is characterized by simple structure, less required input data, and relatively low precision of disadvantage (Amore et al. 2004). Thereafter, the common soil amended equation RUSLE (Revised Universal Soil Loss Equation) was generated in order to expand the scope of application and increase the accuracy. Current software about distributed hydrological model such as AGNPS, SWAT, ANSWER, etc., usually use the RUSLE model in their module of erosion and sediment yield.

The water erosion prediction model WEPP (Water Erosion Prediction Project) was used to simulate the physical process of soil erosion during debris flow and

Fig. 4 The process of debris flow extraction using ETM images. a Raw image, b image of enhanced difference, and c image of debris flow extraction
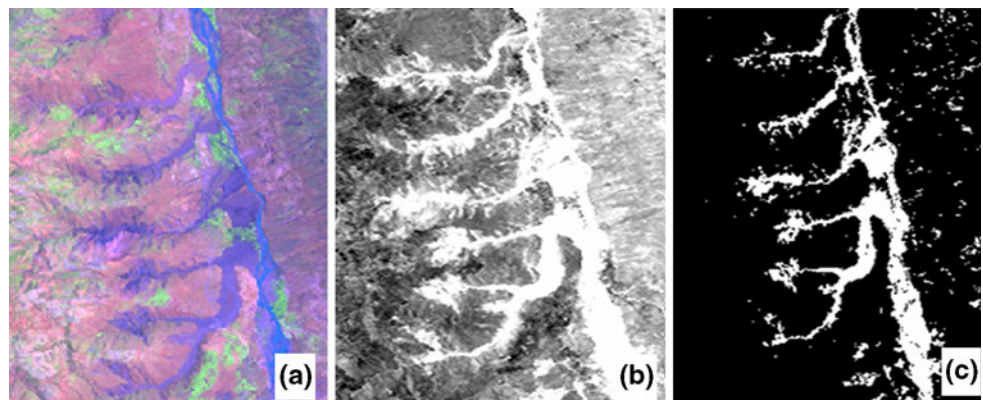
Table 3 Average annual sediment yield observed in the major stations in the lower reach of Jinsha River

| River name	Station	Average annual sediment discharge (10^6 t/a)	River name	Station	Average annual sediment discharge (10^6 t/a)
Jinsha	Panzhihua	42.04545	Yili	Alashaba	0.683333
Jinsha	Qiaojia	164.6038	Zhaojue	Zhaojue	1.047333
Jinsha	Longjie	97.0875	Longchuan	Xiaohuangguayuan	3.758947
Jinsha	Pinshan	242.3103	Mengguo	Gaoqiao	0.1485
Yalong	Xiaodeshi	27.76429	Xima	Dashifang	0.554833
Anning	Wantan	11.75	Xiaojiang	Xiaojiang	6.255
Canyu	Huidong	0.680918	Niulan	Dashadian	12.15083
Heishui	Ningnan	3.5845	Meigu	Meigu	1.807238
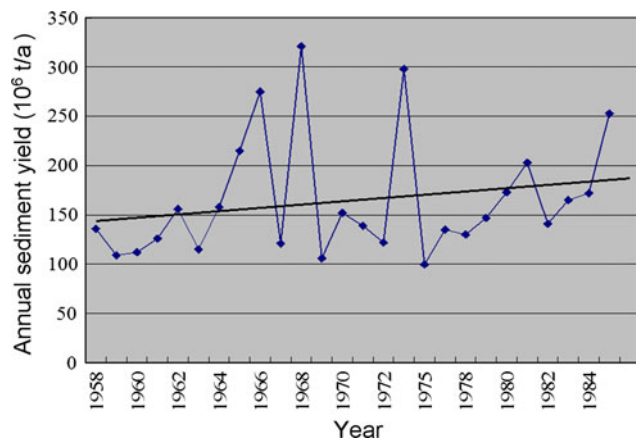
Fig. 5 The changing of sediment discharged into Jinsha River within 30 years (1958–1984) at Qiaojia observing stations

describe its dynamic changes in spatial and temporal manners. The WEPP model requires many parameters with regard to detailed long-term observational data about weather, soil properties, hydrology, land use, farming methods, etc. These parameters were evaluated using remote sensing data and observation data from stations located in the main downstream of Jinsha River.

Results and discussion

Spatial pattern of debris flow distribution

The characteristics of spatial distribution of debris flows in the main downstream of Jinsha River are analyzed based on the spatial database constructed using remote sensing technology. Totally 693 debris flow gullies have been identified in the study area. They directly enter into the mainstream of Jinsha River. Debris flow gullies primarily distribute along some huge fault structures such as Xiaojiang fault, Luzhijiang fault, and Ebian-Jinyang Fault. The spatial distribution of debris flow in each reservoir area is show in Fig. 6.

Wudongde reservoir area

There are 224 debris gullies with a total area of 1,290.9 km^2 located in Wudongde reservoir area. Two subdivisions can be distinguished in this area: one subdivision is from Panzhihua to Longjie and another is from Longjie to Wudongde Dam. Surficial debris flow refers as the basin area less than 0.2 km^2 which is mostly formed by the reasons of lower elevation difference and shorter gully length. In the first subdivision, the catchment are of surficial debris flow is usually small due to the small height difference in the basin (less than 600 m). Therefore, more surficial slope debris flows were distributed in this subdivision than in second subdivisions. 162 debris flow gullies are located in first subdivision while 62 in second subdivision. The difference of spatial distribution of debris flow channels exists between left bank and right bank. In the first subdivision, the number of debris flow gullies in left bank is two times more than those in right bank. The second subdivision shows opposite trend in which the number and areal distribution of debris flow channels located in the right bank are two times more than those in the left bank.

Baihetan reservoir area

There are 169 debris flow gullies with total area of 1,497 km^2. 72 debris flow gullies are distributed in the right bank covering the area of 331.8 km^2. More number of debris flow channels (97) are located in the left bank but cover the area of 691.5 km^2 which might indicate the higher debris flow activities in the left bank.

Xiluodu reservoir area

A total of 172 debris flow gullies are distributed in Xiluodu reservioir area with a total area of 1,654.6 km^2. Three concentration centers can be identified in this area. The average altitude difference from initiation area to toe is
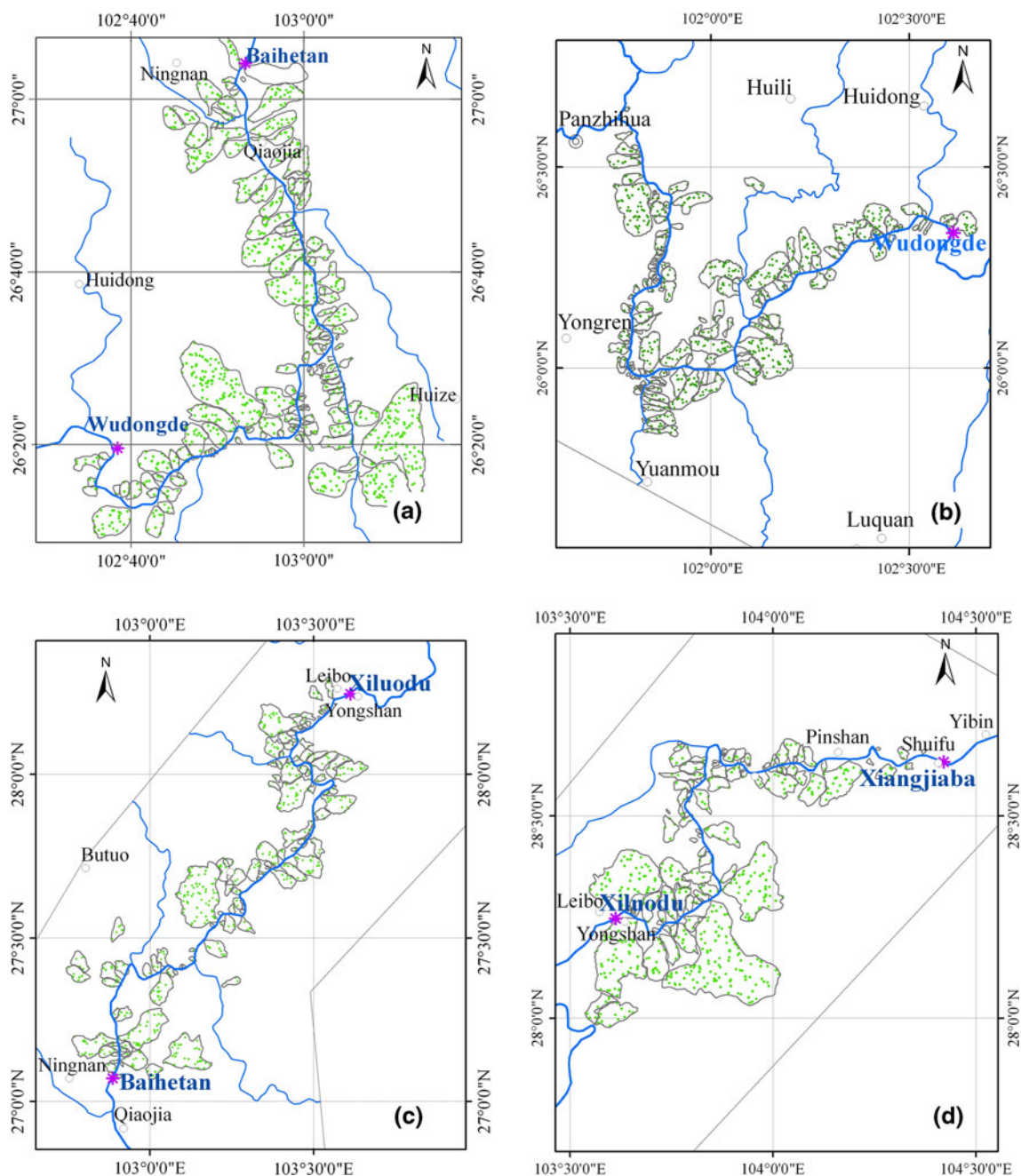
Fig. 6 Spatial distribution of debris flows in each reservoir area. **a** Wudongde, **b** Baihetan, **c** Xiluodu, and **d** Xiangjiaba

2,057 m. Most of the debris flows are of large valley-type which are strongly controlled by the topography.

Xiangjiaba reservoir area

There are 128 gullies with a total area of 1,783.7 km^2 and two distribution centers. The elevation difference from their initiation areas to deposition areas are from 937 to 3,027 m.

The frequency–magnitude relationship between debris flow area and cumulative frequency is shown in Fig. 7.

80% of debris flows have areas less than 20 km^2 in Wudongde and Bahetan Reservoir area while 80% have area less than 50 km^2 in Xiluodu and Xiangjiaba Reservoir area. This might imply that the debris flow activities in Xiluodu and Xiangjiaba Reservoir area tend to have larger magnitude than other areas.

Overall, debris flow gullies in the area tend to be disturbed in groups. A number of distribution centers of debris flows are located in the study area which indicates the high intensity of debris flow activities. The locations of these
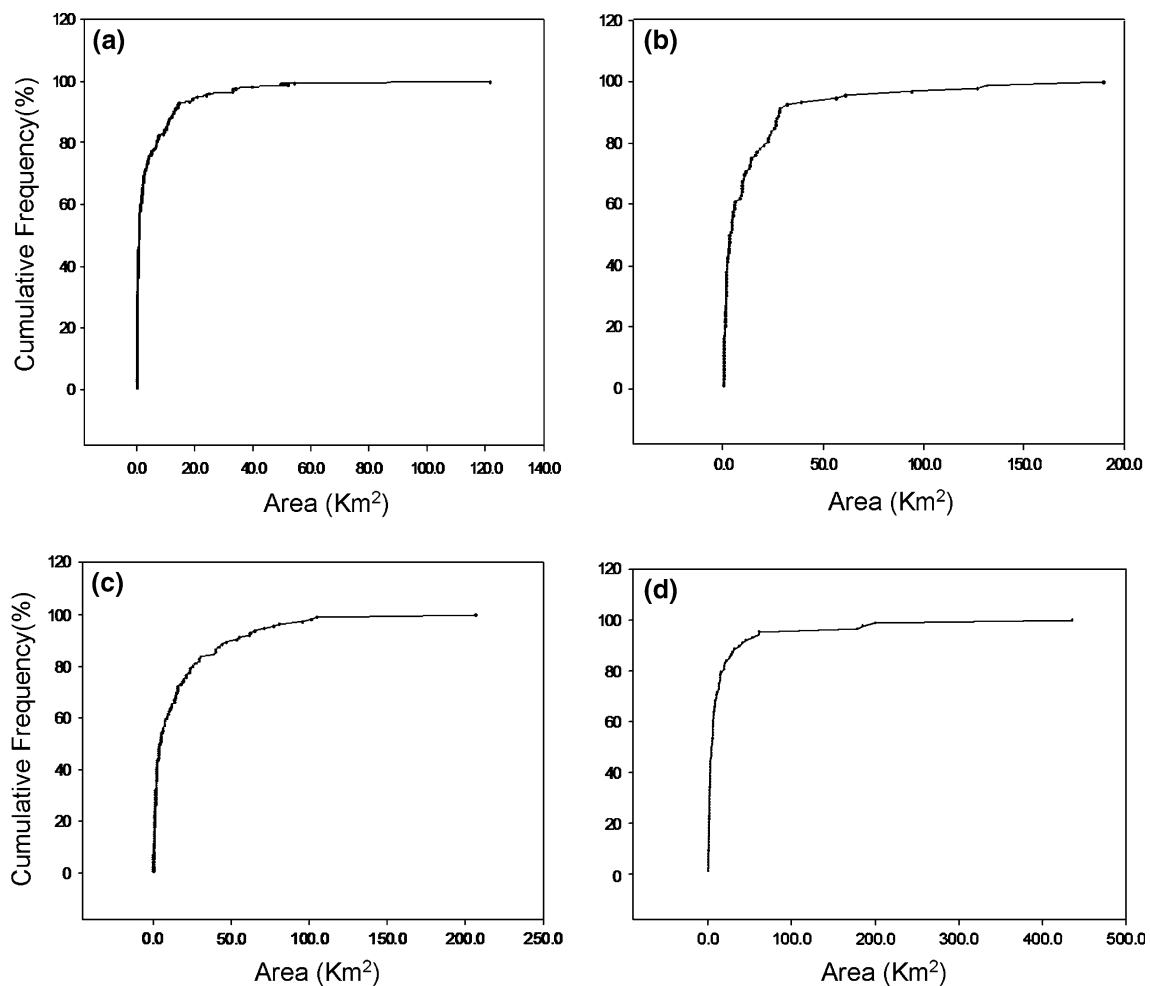
Fig. 7 Frequency–magnitude relationship between debris flow area and cumulative frequency. **a** Wudongde, **b** Baihetan, **c** Xiluodu, and **d** Xiangjiaba

centers are very close or within the epicentral area of earthquakes. This implies that the spatial distribution of debris flow hazard is closely related to the seismic activities. They also tend to be distributed in pairs between left and right bank, especially near the area of Qiaojia, Leibo and Huidong. Some typical examples exist in the Wudongde reservoir area. The Huapingzi gully located in the left bank of Jinsha River, north of Wudongde reservoir area pair with the Bainidong gully on the right bank. The reason for the pairing is because that the Jinsha River is a very young river formed around Oligocene period. During its forming process, it cuts existing rivers which tend to retain their own patterns. As a result, separated sub-rivers have the same or very near confluence point to Jinsha River based on which the debris flow developed tend to distributed in pairs.

The distribution of debris flows is affected by the topographical features. The initiation areas of debris flow are generally located in the middle of mountains and alpine areas where the population is dense and the vegetation was destructed severely. The deposition areas are often located in the dry-hot valley areas. The debris flow deposits are usually washed away quickly and discharged in Jinsha River, The accumulation of fans was not reserved completely. The debris flows are distributed differently along left bank and right bank. More rainfall occurs in left bank than in right bank which results in more severe debris flow activities in left bank.

Sediment yield from observation

Data of nearly 30 years (1954–1985) of sediment observation show that the lower reach of Jinsha River is the concentration area for sediment yield, where 12.8% of the lower reach areas occupy 70% of the whole basin. The statistics on the observation data from each station are shown as follows.

Panzhihua Station

The maximum sediment yield year is 1974 and 1985, with the amount of 56.0×10^6 and 52.7×10^6 t, respectively,

Table 4 Tributary sediment input in S2 and S3

Station	Gaoqiao	Banliyuan	Dashifang	Huidong	Xiaojiang	Alashaba
Longjie–Qiaojia (S2)						
Sediment (10^6 t/a)	0.15	0.0127	0.55	0.68	6.25	0.68

Station	Ningnan	Zhaojue	Luojiahe	Meigu	Xining	
Qiaojia–Pinshan (S3)						
Sediment (10^6 t/a)	3.58	1.05	12.15	1.81	0.13	

which are 20% larger than average value. The sediment yield is stable with years. Yalong River has the maximum sediment yield in 1974 and 1985, with the amount of 45.8×10^6 and 41.9×10^6 t, respectively, which is 65% greater than the average value.

Longjie Station

The largest sediment yield year is 1965, 1968, and 1974 with the observed sediment value of 141×10^6, 152×10^6, and 153×10^6 t, respectively. The average value is 97×10^6 t. The amount of sediment yield increases with years.

Qiaojia Station

The maximum value for sediment transport in 1966, 1968, and 1974 is 275×10^6, 321×10^6, and 298×10^6 t, respectively. The average value is 164×10^6 t.

Pingshan Station

The biggest value year is in 1974 with sediment amount of 501×10^6 t which is two times larger than the average value of 242×10^6 t. The sediment transportation is stable with years.

It can be seen from the observation data that all the stations on Jinsha River had a high value in 1974 which might indicate a possible occurrence of regional flooding.

Relationship between sediment yield and the area of debris flow gullies

Nineteen sand observation stations in the study area are selected for analyzing the relationship between sediment yield and debris flow activity. The timing of these observation data ranges from 1954 to 1985. The selection of these stations follows three criteria: (1) their spatial locations are within or near the study area, (2) their controlling areas are large, (3) long-time series data are available.

Three subdivisions are recognized in the main downstream of Jinsha River: Panzhihua–Longjie (S1), Longjie–Qiaojia (S2) and Qiaojia–Pinshan (S3).

The total length of subdivision of Panzhihua–Longjie (S1) is 95.9 km. It has 97 debris flow gullies with a distribution area of 440.0 km^2 and a density of 1.01 gullies/km. The ratio of debris flow area to the length of subdivision is 4.6 km. Panzhihua observation station is located in the upper part of the subdivision and Longjie station in the lower part. Yalong River and Longchuan River are two tributary rivers for Jinsha River in this section. Two sediment observation stations are located along the Yalong River: Xiaodeshi and Wantan. One station, Xiaohuang-guayuan, is located at Longchuan River. These five controlling observations stations are taken into account.

The average annual sediment observed at Panzhihua station for many years is 42.05×10^6 t/a, and that from Xiaodeshi and Wantan is 27.76×10^6 and 11.75×10^6 t/a, respectively. The sum of sediment from Xiaodeshi and Wantan station is 39.51×10^6 t/a which stands for the average annual sediment yield contributed by Yalong River. Therefore, the multi-year average sediment discharged into Jinsha River is 81.56×10^6 t/a. Xiaohuang-guayuan observation station located in the longchuan River has an average annual sediment yield of 3.76×10^6 t/a for many years. So the total sediment discharged into this subdivision is 85.32×10^6 t/a. And the output sediment observed at Longjie Station is 97.09×10^6 t/a. Therefore, the net sediment, the difference between input and output in this subdivision is 11.77×10^6 t/a. Since most of sediment is caused by debris flow and landslide, dividing the net sediment by debris flow distribution area, a ratio of 2.675×10^4 t/km^2 is calculated indicating the relationship between sediment yield and debris flow distribution area.

Similarly, based on the Table 4, the ratio of sediment yield to debris flow area in subdivision of Longjie–Qiaojia (S2) and Qiaojia–Pinshan (S3) can be calculated as 2.79 and 2.61 separately.

The relationship between sediment yield and debris flow area for these three subdivisions is summarized in Table 5. Sediment yield has a direct relationship with the debris flow basin area which has the stable ratio of 2.6–2.8. The main sediment yield area in the main downstream of Jinsha River concentrated in the subdivision of Longjie–Qiaojia and Qiaojia–Pinshan. Lingjie-Qiaojia has the largest

Table 5 The relationship between sediment yield and debris flow distribution area

Subdivision	Debris flow number	Distribution area of debris flow (km^2)	Debris flow density (n/km)	Annual sediment yield (10^6 t/a)	Ratio of sediment yield to debris flow area (10^4 t/km^2/a)
Panzhihua–Longjie (S1)	162	440.0	1.01	11.77	2.675
Longjie–Qiaojia (S2)	196	2,122.5	0.79	59.2	2.79
Qiaojia–Pinshan (S3)	335	2,252.7	0.675	58.7	2.61

capacity of sediment yield due to the high density of valley-type debris flow gullies. The subdivision of Panzhihua and Longjie is facing the lowest pressure dealing with the sediment in the river although it has the higher debris flow density in terms of number per km. Most of debris flows in this subdivision is of slope-type which have smaller basin area. Due to the high intensity of sediment yield and short debris flow length, the reservoirs of Wudongde and Baihetan are facing larger pressure of siltation problems.

Relationship between bed-sediment load and suspended-sediment load

It is difficult to collect the sample data of bed-sediment load for Jinsha River due to its rapid and deep huge flow turbulence. Sample data were collected near the Xiluodu dam just before the construction began. It showed that the bed-sediment load accounts for 7.8% of the suspended-sediment load. According to this ratio, the annual bed-sediment load is 0.924×10^6 t/a for Panzhihua–Longjie subdivision, 4.66×10^6 t/a for Longjie–Qiaojia and 4.60×10^6 t/a for the Qiaojia–Pinshan.

In order to better understand the relationship of bed-sediment load and suspended-sediment load related to debris flow activity, grain composition and size distribution for the samples of debris flow deposition fans are tested and analyzed. The sampling locations are concentrated along the subdivision of Xiaojiang to Qiaojia along the Jinsha River.

It can be seen from Fig. 8, samples from G9 gully have the largest median diameter which is more than 30 mm. Samples at G2 gullies have the smallest mean grain size which is from 4 to 5 mm and others have grain size ranging from 6 to 10 mm.

According to the observational data from the sediment stations, the median diameter of Qiaojia is 0.045 mm. At the same time, based on the frequency distribution of the sampled data, only 2–20% of the materials in deposition fans have mean particle size less than 0.045 mm. This implies that at least 80% of the debris flow material discharged into river will be transformed to bed-sediment load, and less than 20% to suspended-sediment load. Therefore, the ratio of bed-sediment load to suspended-sediment load caused by debris flows is about 4:1.
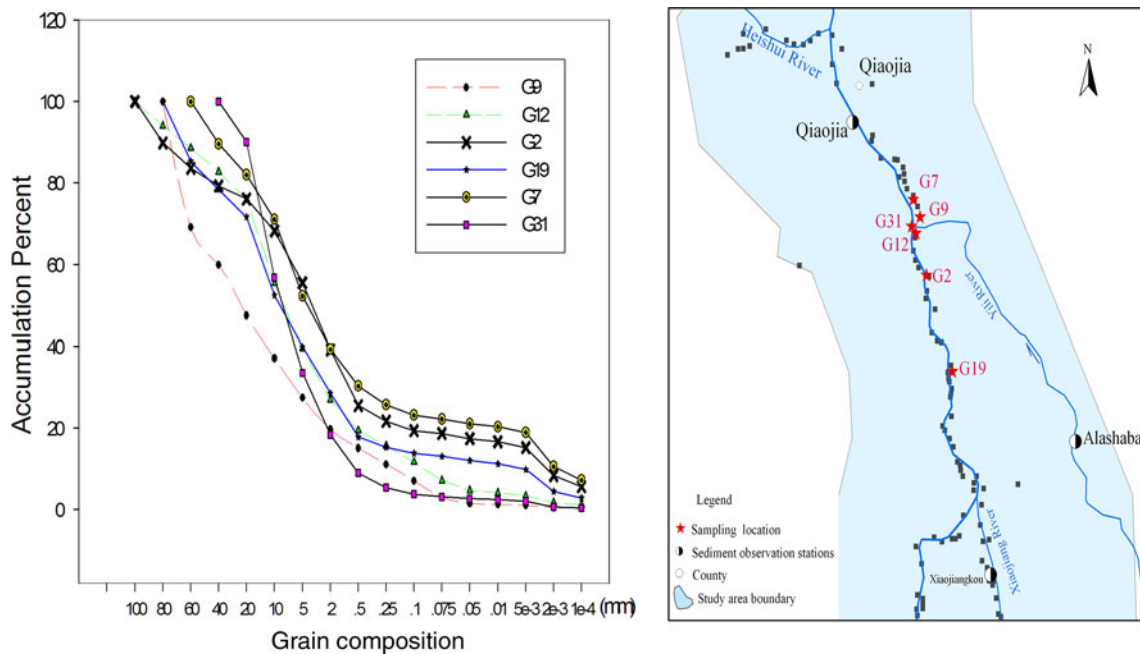

Fig. 8 **a** Grain composition of debris flow fans in Xiaojiang–Qiaojia and **b** sampling location of deposition fan
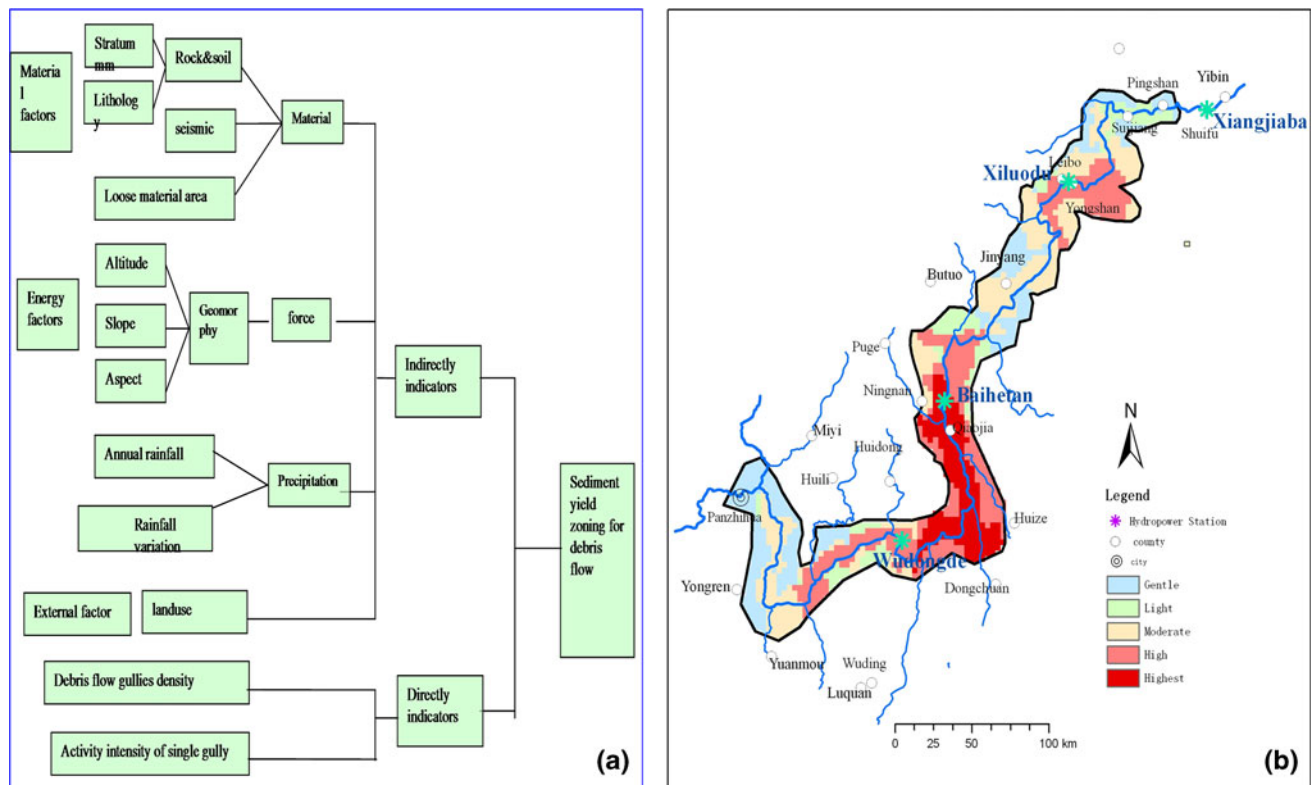
Fig. 9 Map of sediment yield zonation caused by debris flow. **a** Comprehensive factors for sediment yield zoning and **b** zonation result

Potential of sediment yield and zonation caused debris flows

The observed annual suspended-sediment discharged into main downstream Jinsha River is 130.02×10^6 t/a. Based on the above findings, the potential of sediment yield caused by debris flow activities X can be evaluated using the equation.

$$0.2X + Y + H = 130.02 \times 10^6. \tag{1}$$

where X is the annual sediment yield by debris flows discharged into the river, $0.2X$ stands for that 20% of the materials are converted into suspend-sediment, Y is the suspended-sediment generated by the slope erosion and H is the suspended-sediment caused by human activities which was ignored in this case because of weak activity of hydropower or infrastructure construction during the period from 1954 to 1985.

The value of Y was evaluated by empirical relationships. Six degrees of slope erosion are distributed in China: Extreme slope erosion area with the erosion modulus larger than 15,000 t/a; very intensive slope erosion with the modulus of 8,000–15,000 t/a; intensive erosion area with the modulus of 5,000–8,000 t/a where mean value is 6,500 t/a; moderate erosion area with modulus 1,000–5,000 t/a where the mean value is 3,000 t/a; low erosion

area with mean modulus of 750 t/a and slight erosion area with value of 300 t/a. Based on the slope erosion zonation in the study area, the annual suspended-sediment yield by slope erosion is calculated as 67.6×10^6 t/a.

Therefore, the annual potential sediment yield by debris flow activity X is calculated as 0.312 billion ton every year. Given the average bulk density of debris flow materials is 1.5 t/m^3, the total volume of sediment triggered by debris flow discharged into main downstream of Jinsha River is about 0.208 billion m^3/a. After the deduction of suspended-sediment and bed load in the river, the material volume depositing in the reservoir areas is 0.144 billion m^3. An estimation of only 288 years will be needed to fill the full reservoir areas. Such a short period indicates the importance of controlling debris flow hazards in this area.

Sediment yield zoning map is generated by considering the directly factors and indirectly factors (Fig. 9a). The former factors include debris flow gully density and activity intensity of a single gully, and the later factors include material condition, energy condition, stirring condition, external condition, etc. Through spatial modeling in GIS, sediment yield zoning map is obtained (Fig. 9b). Result shows that the areas most severely affected by debris flow are located in the center of Dongchuan to Qiaojia.

It can be seen from Fig. 9, the sediment caused by debris flow activities post bigger threat to the dam sites of

Wudongde and Baihetan than Xiluodo and Xiangjiaba. For example, it has been calculated that the potential amount of sediment caused by debris flows in Baihetan reservoir area is 41.26×10^6 t/a while that in Xiluodo is only 27.2×10^6 t/a. The sequence of reservoir areas facing the threatening intensity by sediment caused by debris flows is Wudongde, Baihetan, Xiluodu, and Xiangjiaba from the highest to lowest.

Conclusions

Debris flow hazard is one of the major concerns in the main downstream of Jinsha River where a number of huge hydropower stations are under construction. The characteristics of debris flow spatial distribution have been studied comprehensively using multi-source and temporal remote sensing technology. An automatic recognition module developed based on ETM provides a solution for fast recognition of debris flow gullies in remote area such as Jinsha River. It helps understand the overall pattern of spatial distribution of debris flows in the study area.

It has been shown that the spatial distribution of debris flows in downstream of Jinsha River is highly affected by a variety of factors including geomorphology, geology, meteorology, land cover, and human activities. The similar geographical and geological conditions result in a common distribution trend of debris flows at different subdivisions in terms of distribution pattern, location, and geometry. However, different subdivisions exhibit different characteristics in term of types of debris flows and their frequency–magnitude relationship. Such a spatial variation should be taken into account in the hazard assessment of debris flows.

The sediment yield caused by debris flow activates has been evaluated using multi-year observation data. Quantitative studies have been performed on the relationship between the sediment yield and the debris flow area. A relatively fix ratio of 2.6 ($\times 10^4$ t/km^2) has been found in different subdivisions of main downstream area. This verifies that the source of sediment discharged into Jinsha River primarily come from debris flow actives. Different subdivisions are facing different sediment threatening caused by debris flows due to their spatial variation.

Grain analysis was conducted for the samples of debris flow fans materials at a number of locations. The relationship between bed-sediment load and suspended-sediment load was analyzed by comparing the grain composition of debris fans with that observed in the controlling stations. It can be concluded that at least 80% of the debris flow materials have been converted into bed-sediment load and less than 20% to suspended-sediment load. Based on that, an estimation of only 288 years will be needed to fill the whole reservoir areas by the sediment

caused by debris flows which indicates the importance of debris flow control in the reservoir area.

The effect of debris flow sediment on the reservoir areas has been assessed using quantities modeling. Zonation map of debris flow sediment potential in the reservoir area has been generated by taking into account a variety of factors. It has been shown that the four dam sites are facing different sediment intensity caused by debris flow activities. The debris flow hazard might be the big concern for the Wudongde dam site.

The studies help understand the spatial distribution of debris flows and the effect of their sediment yield potential which provide important information for effective prevention and mitigation of debris flow hazard in the main downstream area. However, further verification should be conduced in the future studies. The accuracy of assessment can be significantly improved using high resolution and more recent remote sensing technology, such as G-LIDAR or high accuracy RTK GPS measurement.

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