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Magnitude–frequency relations in debris flow

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Abstract Debris flow occurs frequently in mountainous regions in China. Because of the difficulties involved in predicting and catching live debris flows, an assessment of the potential for debris flow is crucial in hazard mitigation. Magnitude–frequency (MF) relations are of special significance in such assessments. In previous studies, MF relations have been inferred by analyzing environmental factors and historical records and using empirical relations. This paper is concerned with the derivation of MF relations at regional and valley scales, using a large database of statistics. At the regional scale, it is represented by the distribution of the valley area, because the area is often taken to indicate the potential magnitude of debris flow. Statistics from over 5,000 debris flow valleys in various provinces in China show that a power law holds for the distribution, i.e., $p(A) \sim A^{-n}$, where $p(A)$ is the percentage of valleys with area A and n varies with region and thus describes regional differences. At the valley scale, a case study focusing on Jiangjia Gully (JJG) was conducted, and the MF relations derived from it were expressed by the distributions of discharge and runoff (i.e., the total volume) of living debris flows observed over the last 40 years. The distributions can be expressed as exponential functions where the exponents vary with the events. These MF relations provide not only a potential quantitative reference for practical purposes but also hint at the intrinsic properties of the debris flow.

Keywords Debris flow · Magnitude–frequency relation · Jiangjia Gully

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Introduction

Debris flow occurs frequently in mountainous valleys carrying large volumes of sediment and boulders. As phenomenon that is intermediate between landslides, rockfalls and fluvial sediment transport, debris flows were first identified more than a hundred years ago (e.g., Stiny 1997), and have been monitored ever since. Since it is a type of geomorphologic hazard, it has been the focus of multidisciplinary research over the last few decades (Beaty 1974; Liu and Mo 2003; Glade 2005; Jakob 2005; Hürlimann et al. 2006). Although many models for debris flow have appeared in the literature (e.g., Takahashi 1981, 2000; Hungr et al. 1984; Coussot and Meunier 1996; Hutter et al. 1996; Davies 1997; Hungr 1997; Iverson 1997; D'Ambrosio et al. 2007), they are still limited in terms of being able to predict details about live debris flows. Therefore, various empirical relationships have been proposed for practical purposes (e.g., Iso et al. 1980; Hungr et al. 1984; Costa 1984; Johnson 1984; PWRI 1988; Rickenmann 1999). These constitute the assessment of debris flow. In practice, two categories of assessments can be distinguished: one for large regions and the other for individual valleys. At the regional scale, one assesses the potential activity and tendency of debris flow; while, in given valleys, parameters such as velocity, discharge, and runoff of a possible debris flow are estimated by semi-quantitative methods, field surveys, and personal experiences (Rickenmann 1999; Chen and Lee 2000; Imran et al. 2001; Parsons et al. 2001; Lin et al. 2002; Liu and Mo 2003; Pasuto and Soldati 2004). Among the most crucial information gleaned is the magnitude–frequency (MF) relation, which is important for hazard mitigation (Liu 1996; Ohmori and Hirano 1988; Fell 1994; Glade 2005). The frequency of debris flow can be described in two ways: in a spatial sense, it is the number (or percentage) of cases of a specified magnitude within the total range of magnitudes observed. In a temporal sense, it is the frequency over time of events or is expressed in terms of return periods (Innes 1985; Van Steijn 1996). At the regional scale, the MF relation can define the debris flow activity (Van Steijn 1996), while in a valley it reflects the variations in activity. Limited by the data available, MF relations have usually been inferred from historic records and field investigations after the events (Rapp and Nyberg 1981; Van Steijn 1996; Rickenmann 1999; Glade 2005). Results obtained in this way are inevitably weak in representing the features of live debris flows. Derived from large data sets, this paper presents the MF relations in a spatial sense. For the regional scale, the MF relation is represented by the distribution of valleys in seven provincial regions in China; while for the valley scale, a case study is carried out for a famous debris flow valley, Jiangjia Gully (JJG) in the southwest of China, and the MF relations are represented by distributions of discharge and runoff. Some new insights into debris flow are obtained, which may compensate for the data issues suffered by previous studies and indicate intrinsic features of debris flows.

MF relations at the regional scale: in terms of valleys

Background and data sources

In areas of severe and frequent debris flows, especially in China, it is necessary to assess debris flow activity on a large scale in order to be able to effectively plan hazard mitigation and mountainous construction work. However, there is a scarcity of data concerning details of debris flows or even of the valleys. Thus, despite the fact that there are many influential factors that are specific to individual debris flows, factors covering large-scale areas are often used, such as features of geology, geomorphology, and climate. Among these, the valley area, together with other planimetric properties, is often the only parameter associated with the valley that can be gained from the topographic maps available. The *Database of Debris Flow in China*, founded by IMHE, CAS (Li et al. 2002), contains more than 8,000 debris-flow valleys, most of which were identified by field surveys and located on topographic maps at scales of 1:10,000, 1:25,000, 1:50,000, and 1:100,000. A debris-flow valley is defined as a valley that has a historical record of debris flow or being under the threat of potential debris flows. Although many events have been recorded, few details about them are known. However, an overall view can be gained for a region by considering the distribution of the valleys. For each valley, the catchment area is measured by a digital planimeter to precisions of up to 0.01 km^2. Seven provincial regions are chosen, including more than 5,000 valleys. The regions are Liaoning and Beijing in the east, and Sichuan, Yunnan, Gansu, Tibet and Xinjiang in the west (Fig. 1, with circles indicating debris-flow sites and black dots indicating dense concentrations of debris flows). Each region is distinctive in terms of geology, geography and climate.

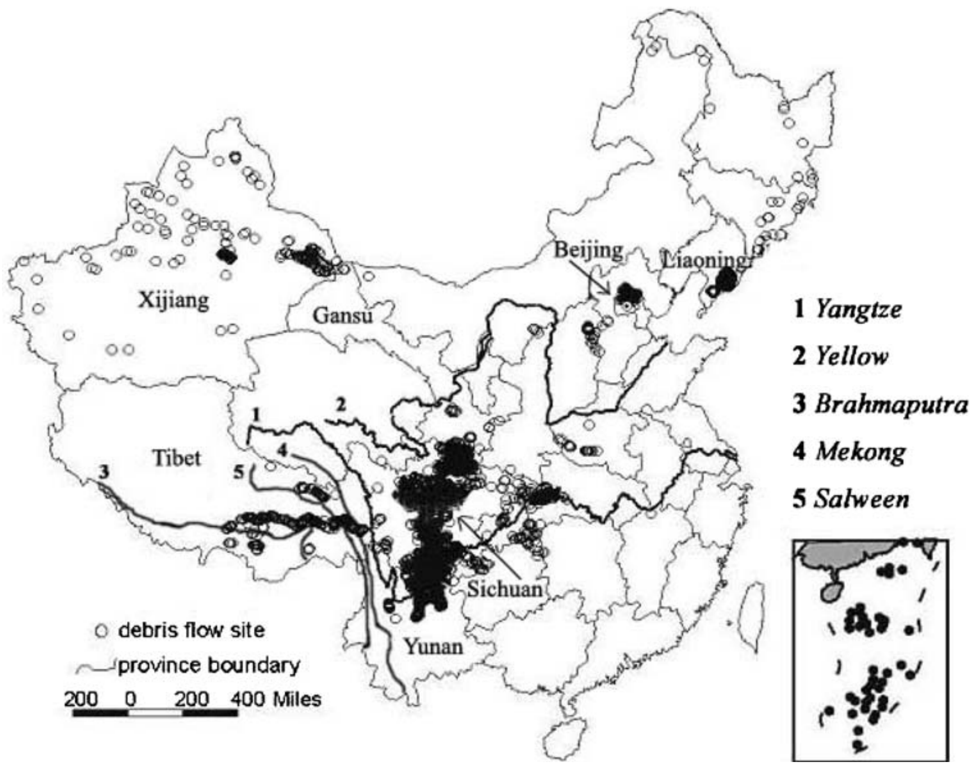
Distribution of valleys

Statistics show that most of the valleys are smaller than 100 km^2 in the west and even smaller than 30 km^2 in the east; the number drops radically as the size increases. Table 1 lists the percentage of the valleys that have areas A in the indicated range for each region. Furthermore, the distribution can be well fitted by a power-law function:

$$p(A) = CA^{-n} \qquad (1)$$

where the constant C and the index n are listed in Table 2. Because each valley exhibits one or at most several occurrences of debris flow, the frequency of valleys also represents the frequency of debris-flow events for a given area. This means that the number of debris flows decreases as the valley area increases. Furthermore, as shown by Table 2, exponents vary remarkably with regions; in particular, the values fall into two domains that correspond to the east and west: bigger in the east (1.96 and 1.84) and smaller in the west (between 0.76 and 1.41). Figure 2a,b display some examples. The variations in the west can be interpreted as being due to the complex geologic and topographic conditions present in that region. As is well known, the east is characterized by hills and plains and is geologically quiescent, while the west, located in the famous Tibet-Qinghai Plateau, is much more tectonically active (for more on the physical geography of China, see, e.g., Zhao 1986). In fact, the valleys in the west are distributed in the largest river systems in China, including those of the Yangtze, Yellow, Mekong, Salween, and Brahmaputra rivers (Fig. 1). Thus, it is possible that the differences between regions, which are associated with the growth of the water system (e.g., Rigon et al. 1994; Rodriguez-Iturbe and Rinaldo 1997) can be characterized by

Fig. 1 A sketch map showing the sources of debris flow distribution data in China



the exponent n, and in this context the exponent can be applied in order to assess debris flow on a regional scale.

MF relation in terms of valleys

Furthermore, the valley distribution also implies an MF relation, because the valley area represents the possible magnitude of the debris flow to some degree. Indeed, especially in engineering practices in China, the debris-flow discharge incorporated into hazard mitigation plans is generally estimated via the peak flood discharge (Kang 1991; Zhou et al. 1991; Ao et al. 2006; Cong et al. 2006), and the flood discharge is hydrologically related to the valley area. Various empirical formulae for flood discharge can be reduced to (e.g., Jarvis 1936; Alexander 1972; Willgoose et al. 1991)

$$Q = KA^m \tag{2}$$

where K incorporates empirical coefficients involving the designated flood frequency and the shape of the valley (Ao et al. 2006). In most cases, the valley is so small that the whole area contributes to the debris flow, as it does to the flood. Then the peak discharge of the debris flow is estimated by including a multiplication factor for sediment content. Thus the valley size represents the possible magnitude of debris flow at the designated frequency of the corresponding flood. Moreover, according to Eq. 2, as the

Table 1 Distribution of debris-flow valleys in the study regions

Valley area A (km^2)	Liaoning	Beijing	Sichuan	Yunnan	Gansu	Tibet	Xinjiang
$0 \le A \le 2$	40%	43.90%	22.14%	27.88%	14.77%	7.11%	32.32%
$2 \le A \le 5$	49.73%	37.65%	33.20%	27.24%	47.27%	40.14%	22.65%
$5 \le A \le 10$	6.37%	10.98%	15.81%	14.10%	14.77%	17.66%	6.61%
$10 \le A \le 20$	3.54%	6.25%	12.72%	11.22%	9.94%	13.30%	11.70%
$20 \le A \le 30$	0.36%	1.22%	5.15%	6.09%	3.13%	7.34%	8.65%
$30 \le A \le 50$			5.51%	4.17%	6.82%	7.34%	4.83%
$50 \le A \le 100$			5.55%	5.45%	2.84%	5.04%	5.85%
$100 \le A \le 200$				3.85%		2.06%	7.38%
Number of valleys	565	657	3067	300	352	435	217

Table 2 The fitting exponents for the area distributions in the study regions

Region	*C*	*n*	Goodness of fit (R^2)
Liaoning	0.7608	1.9657	0.9474
Beijing	0.7377	1.8414	0.9525
Sichuan	0.4652	1.4139	0.8795
Gansu	0.2211	1.0748	0.8220
Yunnan	0.098	0.763	0.7778
Tibet	0.1757	0.966	0.8087
Xinjiang	0.2066	0.8714	0.6795

valley distribution takes the form of a power law, so does the MF relation.

In addition, the total volume of a debris flow or the area of deposition is also evaluated using the valley area (e.g., Iso et al. 1980; Tan 1986; Ohmori and Hirano 1988; Tan et al. 1994; Liu and Tang 1995; Liu and Mo 2003; Liu and Zhang 2004). In some cases, the total volume V is related to the valley area by a log-type relation (Ohmori and Hirano 1988; Liu and Mo 2003):

$$V \sim \log A \qquad (3)$$

This leads to another form of MF relation, i.e., an exponential distribution of the total volume.

One can then use the distribution to assess the risk of debris flow in a large region. In some studies, a valley is artificially assigned a specific weight proportional to the area (e.g., Liu 1996; Liu and Mo 2003), as an index of the magnitude of debris flow, supposing that the large valley has a large debris flow and hence a high degree of risk. Now the distribution suggests that debris flow occurs more frequently in small valleys. It seems more reasonable to take the frequency as the weight of a given area in place of the artificially assigned value. Thus the distribution provides a definite index for assessing debris flows. Following this logic, debris-flow potentials can be compared by finding the distribution of possible valleys.

MF relations in a valley: a case study on JJG

Characteristics of debris flows in JJG

Now, the MF relation of debris flow at a regional scale is expressed by the distribution of valleys and is characterized by exponents that vary with region. In the following, the MF relations are explored for a specific valley.

This case study focuses on JJG. Located in the southwest of China, JJG, as shown by Fig. 3 (Chen et al. 2005), is famous for its high frequency and wide variety of debris flows and has drawn worldwide attention for decades (e.g., Li et al. 1983; Davies 1986, 1990; Davies et al. 1991; Li et al. 2003, 2004; Cui et al. 2005). An observation station (the dense triangle in the photo in Fig. 3) was set up in the 1960s. With an area of close to 50 km^2, JJG is rather large with regards to debris flow. In fact, debris flows come mostly from the tributaries shown in the square in Fig. 3, and these tributary flows are often observed to stop and deposit halfway (Li et al. 2004). This coincides with the fact, revealed by the distribution of valley areas, that debris flow occurs more frequently in small valleys. Because of the varieties of tributaries and

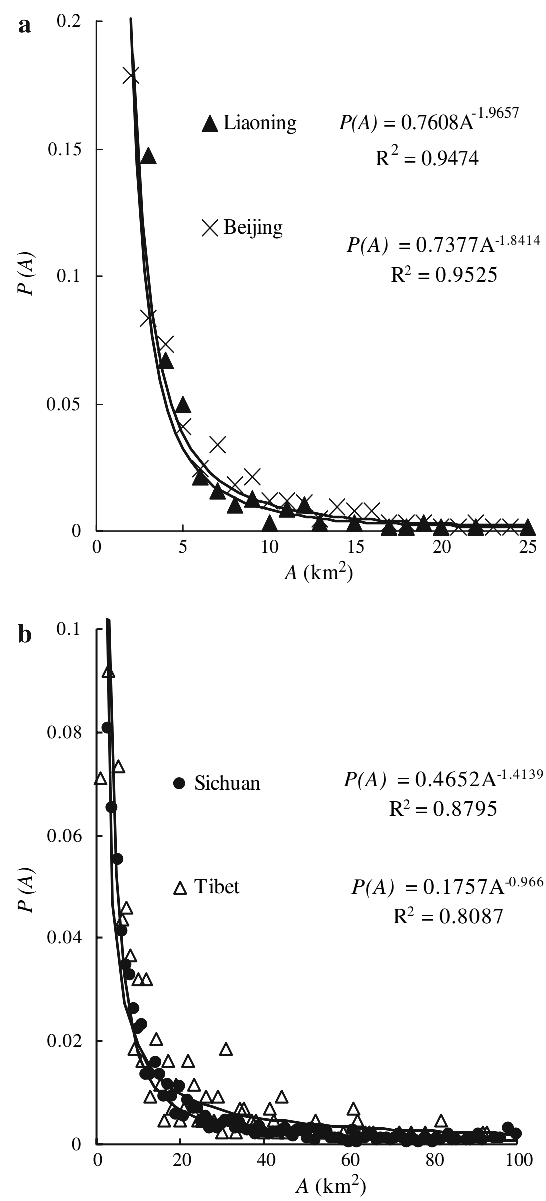


Fig. 2a–b **a** The area distributions of debris-flow valleys in Liaoning and Beijing. **b** The area distributions of debris-flow valleys in Tibet and Sichuan

the discontinuities in mass supplies, debris flow moves in intermittent surges, i.e., as a flow body with a distinguishing front and a finite volume, which is a universal phenomenon in debris flow (e.g., Sharp and Nobles 1953; Iverson and Lahusen 1993; Major 1997). In JJG, surges always occur in succession, with time intervals ranging from tens to hundreds of seconds. Between successive surges, concentrated flows with much smaller densities and discharges occur (Li et al. 2004, 2005). This series of surges constitutes an event of debris flow. Thus a debris flow is a process of multiple peaks of discharge. Dynamic observations are conducted as surges pass the fixed sections *AB* and *CD* (Fig. 4). The discharge is calculated by measuring the average speed of a surge between these sections. The runoff of a surge is the product of the measured discharge and the duration (ranging from 10 to 100 s) of the surge (Kang et al. 2006).

In the last 40 years, more than 400 events of debris flow have been recorded for JJG, and data have been logged for nearly 10,000 surges. These uniquely observational data enable us to gain a comprehensive understanding of debris-flow surges (Li et al. 2003, 2004; Liu et al. 2007). Limited by observational conditions (especially in the 1960s through to the early 1980s), the data are incomplete for many events. Nevertheless, the events containing complete series are sufficient for statistical analysis. In this study, the runoff and discharge data are used. It is expected that the runoff distribution for various events represents the usual MF relation, while the distributions of runoff and discharge within an event reflect the variation.

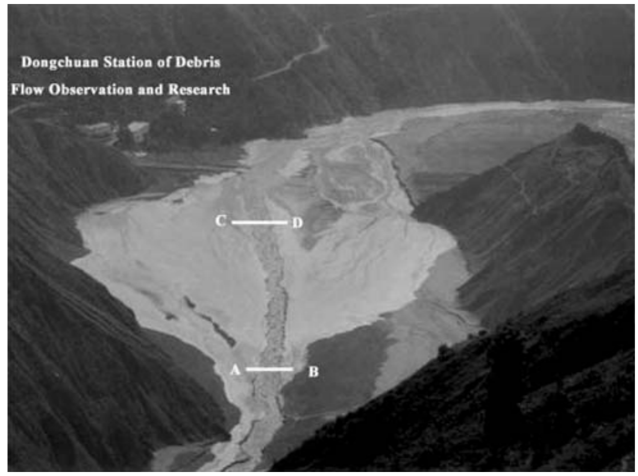
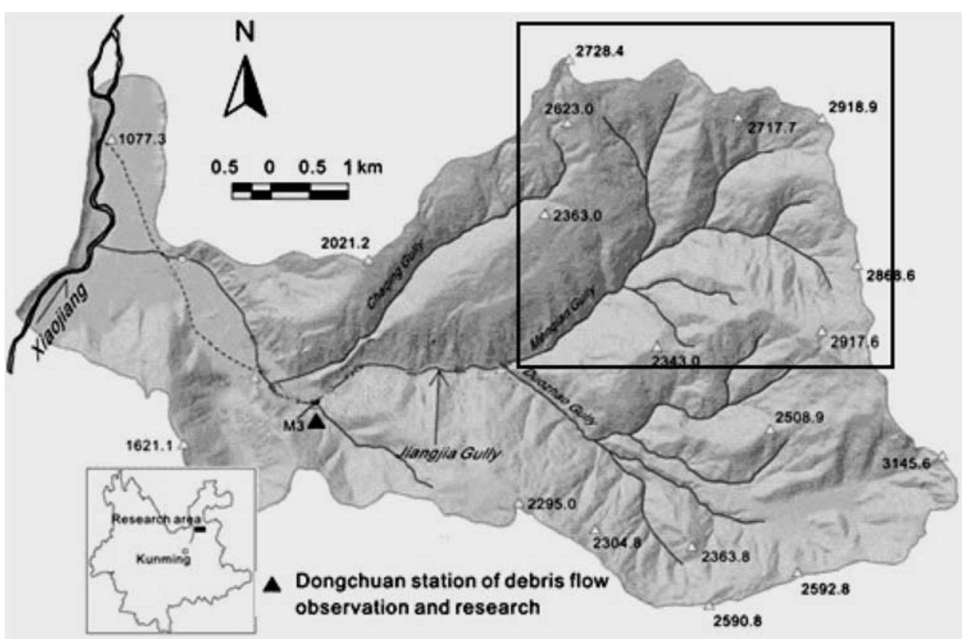


Fig. 4 The cross-sections of debris flow observed at the station

Runoff distribution for debris-flow events

One hundred and fifteen events with complete observations are used here for statistic analysis. The runoff *R* for each event is the sum of all the surges involved, excluding the intermediate concentrated flows, which are not actually debris flows (Li et al. 2005). The MF relation can be expressed in the form of an exceedence probability, i.e., a cumulative distribution; the percentage of events with runoffs that are larger than a given value, $p(>R)$. This type of distribution has been widely used in the geosciences (Hergarten 2002); since it is the integral form of the usual $p(R)$, the percentage of events at a given runoff, it can

Fig. 3 Debris flow in JJG, beginning in the *rectangular area* and observed at the delta point of the station



conceal the effects of data fluctuations and thus is well-suited to uncovering regulation. The result is shown in Fig. 5, which displays an exponential curve of the form:

$$p(>R) = 0.836\exp(-0.0358R),\ (R^2 = 0.9657) \qquad (4)$$

This relation quantifies the general findings that frequency decreases as magnitude increases. In most cases, no data are available to establish such a relation, but it is likely to hold generally for intrinsic properties, for relations of this form have been universally observed for many hazardous events, such as floods and earthquakes (Turcotte 1997).

MF relation for individual debris-flow events

The MF relation for the runoff for an event gives an overall estimate but tells us nothing about the details within individual events. The distribution of the runoff or discharge from the surges within an event is expected to exhibit the spatial and temporal patterns of the live debris flow. In the following, 20 events with relatively large numbers of surges (i.e., 80 or more) are chosen for statistics. The cumulative distribution of the surges is considered for each event, and the following exponential function is found to be well-satisfied:

$$p(>x) = C\exp(-kx) \qquad (5)$$

where x indicates either the discharge (Q) or the runoff (R). Figures 6 and 7 show several examples of these exponential curves, and the statistical results are listed in Table 3, where values of R^2 close to 1 indicate satisfactory fitting (the numbers shown in the "events" column and in the figures indicate the dates of the events; for example, event 870823 corresponds to August 23, 1987). For reference in the discussions below, the maximal values of the runoff (R_m) and discharge (Q_m) for each event are also listed in the table.

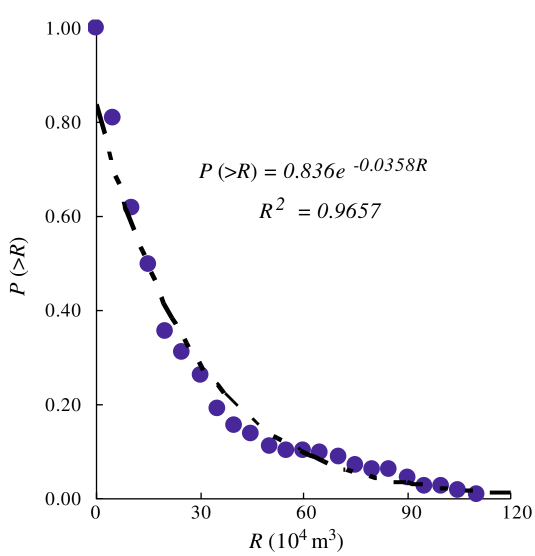


Fig. 5 Distribution of runoff for debris flows in JJG

Implications of the exponent

The distribution may represent the spatial characteristics of the surge series because, as observed in the source area of JJG, each event contains surges from different tributaries. Furthermore, it is also closely related to the temporal pattern. The discharge fluctuates remarkably during an event, as shown by Fig. 8, which presents events 890802 and 870823 (for comparison, in each event the discharge is normalized up to the maximal value, and the straight lines—solid or dotted—indicate the average discharge). No two events are similar, but they do have several features in common: each event consists of many peaks followed by a variable number of troughs; peaks are much higher than the average level; peaks occur rather randomly during the event. Intuitively, these features can be ascribed to the supplies of debris-flow materials and the local initiation of soil failures in the source areas. In fact, field monitoring and experiments in JJG have provided a live scenario. That is, small-scale landslides and soil failures occur randomly on and off the slopes in the upper tributaries, turn into flows in the channels, and then, after sometimes assimilating or depositing sediments on the channel bed, join up with the mainstream in the lower reaches. It is the spatial and temporal patterns of tributary failures and flows that lead to the observed features of the surge series. Thus, the exponent characterizes the event (surge series), and the variation in the exponent coincides with the fact that these events have different origins. On the other hand, the fact that all of these events can be cahracterized by exponential distributions, although with different exponents, suggests that there are some underlying dynamics behind the

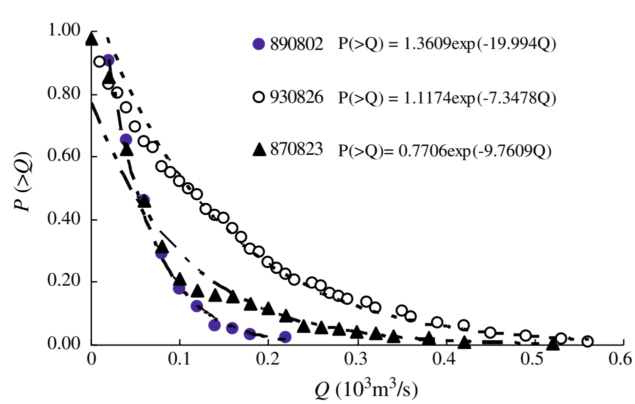


Fig. 6 Distribution of surge discharges

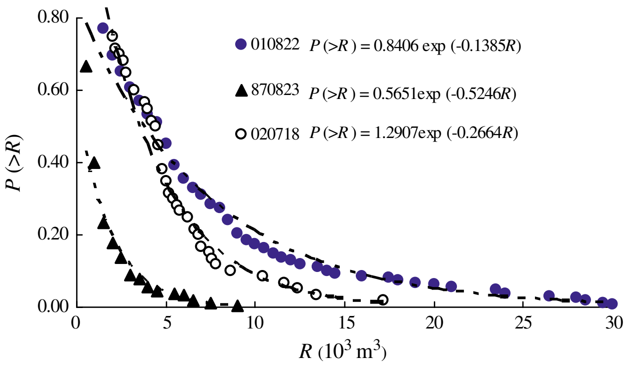


Fig. 7 Distribution of surge runoff

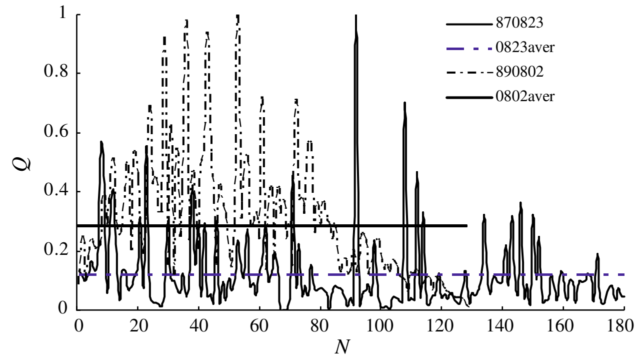


Fig. 8 Hydrographs of debris-flow events with long surge series

scenario, just as the existence of power laws suggest the same for self-organized systems (Bak et al. 1988; Hergarten 2002). A great deal of other evidence for this has also been revealed [Li Y (2004) Internal research report for the National Natural Science Foundation of China].

Furthermore, there is a certain relation between the exponent and the discharge series. It is notable that the biggest exponent (19.994) appears for the event 890802, the maximal discharge of which (238.2 m^3/s) is the smallest among all of the events involved, while the smallest exponent (1.3577) appears for the event 980709, the maximal discharge of which is the largest (2913.9 m^3/s). This suggests that the exponent is related to the maximal discharge. Indeed, as shown in Fig. 9, there is a power law here,

$$k_Q = 5361.2 Q_m^{-1.0126} (R^2 = 0.9134) \quad (6)$$

where k_Q is the exponent and Q_m is the corresponding peak discharge of the series. This becomes more remarkable when one notes that similar relations do not occur for runoff. The Q_m then seems to play a dominant role in the surge series. Actually, Q_m has been found to govern the persistence and decay of the surge series (Liu et al. 2007).

This finding is especially significant in that a surge series can be simply reduced to the maximal discharge for assessment. The maximal discharge can be empirically determined, for example, using rainfall data and hydrological methods. In practice, Q_m is also the most crucial parameter in engineering designs for debris-flow prevention.

Table 3 Exponents for the distributions of discharge and runoff

Events	k_R	R^2	R_m (m^3)	k_Q	R^2	Q_m (m^3/s)
870823	0.5246	0.9753	51,023	9.6102	0.984	728.9
890727	0.9235	0.9814	48,865	5.3131	0.9817	740.9
890802	0.093	0.9435	5,616	19.994	0.9832	238.2
900620	0.0809	0.8793	116,640	14.748	0.9852	467.8
910717	0.1697	0.9784	37,196	4.1897	0.9677	1319.4
910813	0.1398	0.9735	58,908	7.7798	0.9842	801.4
920717	0.1577	0.9597	19,659	4.1613	0.9718	1053
930826	0.2723	0.9658	17,729	7.3478	0.9837	571.9
940616	0.0744	0.9055	122,938	4.1613	0.9783	1382.5
940625	0.1602	0.9751	53,572	2.4048	0.986	2027.8
940702	0.3571	0.981	13,009	6.3812	0.9457	929.2
980709	0.0997	0.9886	67,818	1.3577	0.9202	2913.9
990810	0.3573	0.9509	12,485	7.1263	0.906	756.8
990825	0.3283	0.9939	36,200	3.5604	0.9679	1350
000809	0.3397	0.9521	14,921	4.284	0.9896	1133.1
010805	0.2799	0.9552	18,691	6.3497	0.9606	747
010822	0.1385	0.9702	31,083	3.8273	0.9372	1278.9
020718	0.3675	0.9647	12,852	4.3628	0.9242	856.8
030611	0.2664	0.9832	31,216	3.0968	0.97	1425.1
040731	1.4784	0.9254	2,825	13.577	0.9679	279.8

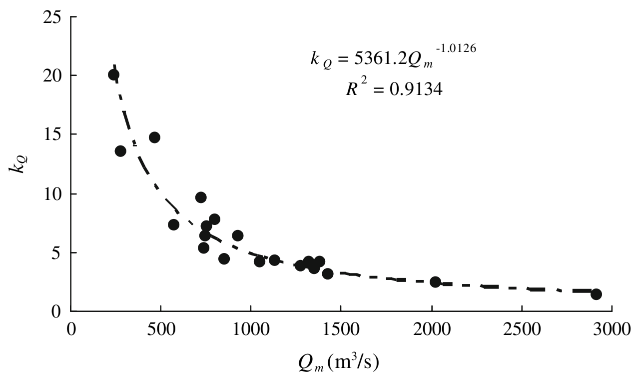


Fig. 9 Relation between the exponent and the maximal discharge

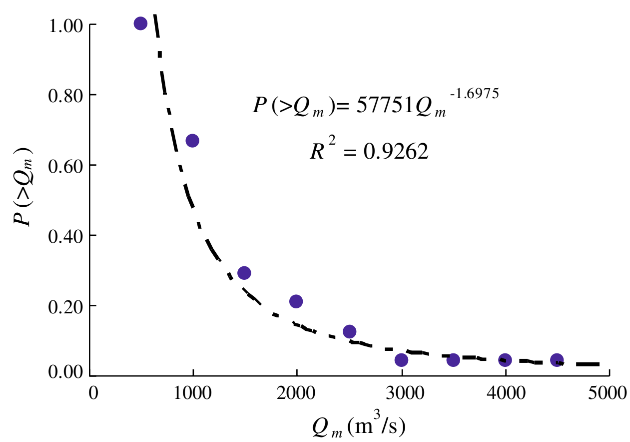


Fig. 10 Distribution of annual maximal discharges

To summarize, a debris-flow surge series (or event) is characterized by its exponent and can be represented by its maximal discharge. As an application, consider the maximal discharges in the JJG since the 1960s. The cumulative distribution is again subject to the power law (see Fig. 10)

$$p(>Q_m) = 57751Q_m^{-1.6975}(R^2 = 0.9262) \quad (7)$$

This is another MF relation which reflects the long-running characteristic of debris flows in a valley. If one had data (long series of observations) on other valleys, comparing the exponents might provide interesting insights into the variations in debris flow under different conditions.

Conclusions and discussion

The MF relationships of debris flow have been explored at the regional and valley scales using large databases of observational data. These relations numerically exemplify the usual observations concerning magnitude and frequency. At the regional scale, the MF relation is represented by the distribution of valley areas, because the area is practically a measure of the potential magnitude of debris flow. The distribution satisfies a power law with an exponent that varies between regions, showing that the frequency of debris flow decays as the valley size rises, although at different rates in different regions.

At the valley scale, investigated via a case study of JJG, MF relations in terms of discharge and runoff can be expressed by exponential functions with exponents that vary between events. The variation of the exponent describes the intrinsic properties of the debris flow in that it is related to the maximal value Q_m of the event. This means that Q_m plays a dominant role in the debris flow process. Accordingly, assessing the magnitude of a debris flow can be reduced to determining the value of Q_m, which, in turn, satisfies the same MF relation.

Considering the similarity of the MF relations for different events and their relation to the temporal features of the surge series, it is tempting to speculate that there might be some dynamics that underlie the live debris flow.

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