

Rainfall thresholds of the debris flows based on various rainfall intensity types in Beijing

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Abstract

Empirical rainfall thresholds derived from various types of rainfall intensities have widely used in characterizing rainfall conditions that cause debris flows and landslides. However, few works have studied the differences among these various thresholds, due to limited information on the instantaneous intensity triggering debris flows. The detail records of the storms on 21 July, 2012, 20 July, 2016, and 16 July, 2018, together with the occurrence time of debris flows, provide an opportunity to evaluate the thresholds based on various rainfall intensities. Based these data, a new rainfall threshold of debris flows is derived from the instantaneous rainfall intensity in Beijing. At the same time, the thresholds based on average rainfall intensities as used in most previous studies, including the average over the periods from the beginnings of rainfall to the occurrences of the debris flows and over the whole period of the rainstorms, are reconstructed. The result shows that the instantaneous rainfall threshold has a higher ability in separating the rainstorms inducing from those without reducing debris flows than those derived from average intensities, indicating a high accurate of the instantaneous threshold. Our data also indicate that the debris flows in Beijing should be triggered by the concert works of rainfall intensity and cumulative precipitation. Only when enough water to infiltrate, saturate, mobilize the debris sediments, and sufficient high water flows and surges caused by intensive storms to incorporate and retain the mobilized sediments, are satisfied simultaneously do the debris flows occur.

1. Introduction

Debris flow is the major geo-disasters in Beijing, and many heavy disasters occurred in the past. The debris flows in 1888 destroyed 39 villages and caused a great loss of both human lives and assets. According to the geo-disaster survey of Beijing, more than 9 hundreds sites including many villages and tourism sites are under thee threaten of debris flows. Therefore, the early and accurate forecast of debris flows is of special significance for the disaster prevention and mitigation in Beijing. Though many factors, such as geological and geomorphological characteristics, compositions of sediments, and vegetation cover, have a potential impact on debris flows, it is well known that intensive storm is often the initial trigger (David-Novak et al. 2004, Guzzetti et al. 2007, Iverson 1997, Kean et al. 2011). As a result, the rainfall threshold becomes the key to forecast debris flows and landslides (Baum and Godt 2010, Fausto et al. 2008).

The empirical model is the method widely used to estimate rainfall thresholds (Aleotti 2004, Caine 1980, Crosta and Frattini 2001, Guzzetti, Peruccacci, Rossi and Stark 2007, Saito et al. 2010, Tang et al. 2012, Wiczorek et al. 2000). This threshold is established based on statistical analysis of the past rainstorms causing debris flows, mainly based the relationships between rainfall intensities and durations of the storms (Caine 1980, Guzzetti, Peruccacci, Rossi and Stark 2007). Therefore, the definition of rainfall intensity is the key to establishment of empirical model and forecast debris flows (Guzzetti, Peruccacci, Rossi and Stark 2007). There are various types of rainfall intensities, which have different geophysics implications (Guzzetti, Peruccacci, Rossi and Stark 2007). Theologically, the thresholds derived for

various intensities should have some differences. However, few works have evaluated the differences among the various thresholds before.

Rainfall intensity is the amount of precipitation accumulated in a period, or the rate of precipitation in a period, most commonly measured in millimeters per hour. The average rainfall intensity is the main type of intensity used to establish the empirical model, due to lack of the information about the occurrence time of debris flows. Based on the length of observation periods, average intensities can be divided into the average intensity over hours (peak intensity), days or longer periods, such as average over the period of whole rainfall or over the durations before the occurrences of debris flows (Guzzetti, Peruccacci, Rossi and Stark 2007). The peak intensity indicates the average rainfall rate of the maximum rainfall period, while the average over long periods reflects the “average” value that underestimates the peak (maximum) rainfall rate occurred during the observation period (Guzzetti, Peruccacci, Rossi and Stark 2007). However, both the average and the peak intensity have limitations in characterizing the rainfall threshold triggering debris flows. Many studies showed that the occurrences of debris flows coincided with periods of intense rainfall during a rainstorm (Kean, Staley and Cannon 2011, McCoy et al. 2010, Parise and Cannon 2012, Tang et al. 2011). In situ measurements of debris flows in southern California suggested that the timing and magnitude of the debris flows were controlled consistently by short duration (≤ 30 min), high intensity rainfall (Kean, Staley and Cannon 2011). For the peak intensity, some studies, including the research of Beijing (Ma et al. 2018, Wu 2001), showed that the occurrences of debris flows didn't always correspond to the maximum rainfall intensity. Therefore, the research on the instantaneous rainfall intensities, which coincide to the occurrences of debris flows, is of special significance in accurately estimating the rainfall thresholds. However, to our knowledge, few studies as such have been reported in previous studies.

Three extreme storms occurring on 21 July, 2012, 20 July, 2016, and 16 July, 2018, caused serious debris flows in Beijing. The detail processes of the storms including their spatial and temporal changes have been registered by the intensive automatic weather stations, FY-2E infrared images, and Doppler weather radar (Lei et al. 2020, Yang et al. 2018, Zhong et al. 2015). Furthermore, the occurrence time of the debris flows was well known. This provides the first opportunity to test the reliability of the rainfall thresholds derived from various rainfall intensities and make a deep insight on the dynamics of debris flows in Beijing.

This paper made a systematic analysis on the evolution of the three storms, particularly the changes of rainfall intensity and precipitation, and its association with the occurrence of debris flows. A new rainfall threshold was established based on the relationship between the instantaneous rainfall intensities (I_i) and the rainfall durations before debris flow occurrences by the empirical model (Caine 1980, Guzzetti, Peruccacci, Rossi and Stark 2007). The rainfall thresholds based on the average intensities, including the average over the periods before the occurrence of debris flows (I_b) and over the whole rainstorm durations (I_w), were also established. The accurate of different rainfall thresholds was evaluated through comparing their abilities in separating the storms inducing debris from those without causing debris flow.

At the same time, the dynamic of debris flows were discussed based on the intensities and precipitations triggering the debris flows.

Geological Setting And Methods

Beijing is located at the northern tip of the North China Plain, near the meeting point of the Xishan and Yanshan mountain ranges. The city of Beijing lies on low and flat land, which is bounded by Xishan Mountain to the west and Yanshan Mountain to the north. The Yanshan and Xishan ranges meet at Nankou, in Changping District, northwest of the city. Xianshan belongs to Yanshan mountain range, which runs a north-south up the spine of Hebei province. Xishan covers nearly all of Fangshan and Mentougou Districts, and the western part of Haidian. The highest peak in Beijing (Lingshan with an altitude of 2303m) is located in Xishan mountain areas. The high mountain meadows and river gorges, such as Shidu and Juma River, are developed across Xishan. To the north of Beijing city, Yanqing and Miyun Counties, and Huairou and Pinggu Districts are located in the Yanshan range running from west to east across north Hebei Province.

Faults, folds, bedrock fissures are developed intensively in the mountain areas of Beijing. This tectonic factor, together with rock weathering, results in a large amount of unconsolidated sediments accumulated in the mountain valleys, providing enough debris materials for debris flows. Therefore, the debris flows occur mainly in these mountain areas (Wang 2008, Wu 2001, Zhong et al. 2004).

The climate of Beijing is semi-humid continental climate, which is controlled by Asia Monsoon, characterized by hot, humid climate in summer and dry, cold climate in winter. The annual average precipitation is around 600 mm with a little high precipitation in the northeast and southwest areas. The rainfall concentrates in summer season, particularly from June to August, the precipitation of June-August accounts for more than 80% of the annual total precipitations. Almost all of the debris flows of 1949-2018 occurred during the interval from June to August (Wang 2020).

The detail processes of the storms occurred on 21 July, 2012, 20 July, 2016, and 21 July, 2018 are reconstructed based on continuous monitoring data of the meteorological stations, which are located in or nears the areas where debris flows occurred. The occurrence times of debris flows are taken from news reports, geo-disaster survey reports, and the interview with local residents.

Extreme storms and debris flows

The rainfall patterns are different between each other for the rainstorms occurring on 21 July, 2012, 20 July, 2016, 21 July, 2018. The duration of the rainstorm on 21 July, 2012 is the shortest one of the three storms. It began on 21 July at 9:00 and stopped on 22 July at 4:00 with a duration of 19 hours. The average precipitation is around 170 mm with the maximum cumulative precipitation of 541 mm (a 500-year storm scale) in Heibeizhen of Fangshan District. 7 and 8 meteorological stations detected a precipitations within 24 hours reaching a 100-year and 50-year storm scales, respectively. The storm on 20 July, 2016 has the largest average precipitation (203 mm) of the three storms, reaching the level of a

100-year storms. The duration of this storm is 55 hours, longer than that in 2012. The maximum cumulative precipitation (422 mm) also occurred in Fang District (Nanjiao station). The precipitation within 24 hours reaching the level of a 100-year storm were detected by 5 stations, and the 50-year storm by 10 stations. The storm on 16 July 2018 experienced a longer time intervals compared to the storms in 2012 and 2016. It began on 15 July at 15:00 and lasted about 60 hours. Compared to the long duration, the average precipitation (102 mm) of this storm is the smallest one of the three storms. The maximum cumulative precipitation of 351.3 mm occurred in the region of Xibailianyu, Miyun District.

Though the total precipitation brought by the rainstorm on 20 July, 2016 is larger than the storm on 21 July, 2012, the damage and loss caused by the later one is much serious. Debris flows and landslides occurred mainly in Fangshan District, where a total of 22 debris flows and 10 landslides were triggered by the storm in 2012 (Fig.1). The large scale debris flows and landslides occurred in Heibeizhen (7 events), Xiayunling (13 events), and Nanjiao (3 events) coinciding to the heavy storms (Fig.1). The debris flows caused by the rainstorm on 20 July 2016 and 16 July 2018 is few. Each rainstorm causes only one debris flows, which occurred in Jiangxintai, Fangshan District and Xibailianyu, Miyun District, respectively.

Discussion

Rainfall intensities and durations triggering debris flows

Fig.2 displays the changes of rainfall intensities and the precipitations with time, and the occurrence time of the debris flows. All of the debris flows occurred during the periods with high rain intensities, though they are not always the maximum values. The rainfall intensities coinciding to the debris flows range from 48.5 to 98.9 mm/h for the rainstorm on 21 July, 2012, and they are 46 mm/h and 69.1 mm/h for the storms of 2016 and 2018, respectively. For debris flows caused by the storm of 2012, the cumulative precipitations from beginning of rainfall to the occurrences of debris flows changes from 128.4 to 190 mm, while they are 217-226.6 mm and 174-226 mm for the debris flows of 2016 and 2018, respectively. The rain fall durations before the debris flow occurrence show a significant difference among the three rainstorms. The debris flow triggered by the rainfall with the longest duration (15 hours) occurred on 20 July, 2016, while the debris flow induced by the shortest duration rainfall (5 hours) presented on 16 July, 2018 (Fig. 2). The rainfall durations of the debris flows in 2012 change little among various sites, centering around 8-9 hours. The rainfall intensities show a decreasing trend with increased cumulative precipitations. The rainfall intensity is only 46 mm/h with a cumulative precipitation of 217.6 mm for the debris flows in Nanjiao site, while it is as high as 98.9 mm/h corresponding to the cumulative precipitation of 180 mm for the debris flows in Fangshan site (Fig.2).

Rainfall thresholds based various rainfall intensity

For the rainfall-induced debris flows, a rainfall thresholds is defined by rainfall reaching or exceeding a hydrological condition that is likely to trigger a debris flow (Guzzetti, Peruccacci, Rossi and Stark 2007). It has been demonstrated that rainfall-induced debris flows and landslides are closely related to rainfall intensities and durations (Caine 1980, Cannon et al. 2008, Fausto, Silvia, Mauro and P. 2008, Guzzetti,

Peruccacci, Rossi and Stark 2007, Peruccacci et al. 2017, Rossi et al. 2017, Saito, Nakayama and Matsuyama 2010). Therefore, intensity-duration model (I-D) is the most common method to estimate rainfall thresholds (Baum and Godt 2010, Fausto, Silvia, Mauro and P. 2008, Guzzetti, Peruccacci, Rossi and Stark 2007, Saito, Nakayama and Matsuyama 2010). I-D threshold has the general form:

$$I=c+a \times D^b$$

where I is rainfall intensity and expressed in millimeters per hour, D is rainfall duration and expressed in hour, c, a and b are parameters. In most cases, c is often taken as 0 (Guzzetti, Peruccacci, Rossi and Stark 2007), and the equation is a simple power law. The I–D thresholds are usually obtained by drawing minimum-level lines to the rainfall intensity (Y-axis) and duration condition that causes debris flows and landslides (X-axis) shown in Cartesian semi-logarithmic, or double logarithmic coordinates (Guzzetti, Peruccacci, Rossi and Stark 2007, Saito, Nakayama and Matsuyama 2010).

In this study, we establish various I-D models based on three types of rain intensities: the instantaneous intensities (I_i), average intensity (I_a) over the periods from the beginning of the storm to the debris flow occurrence (D_a), and average over the whole storm (I_w and D_w). The I-D models derived from different rainfall intensities by the methods of Caine (1980) and Guzzetti et al. (2007, 2008) are:

$$I_i=198 \times D_a^{-0.795} \text{ (} I_i\text{-}D_a \text{ threshold)}$$

$$I_a=59 \times D_a^{-0.717} \text{ (} I_a\text{-}D_a \text{ threshold)}$$

$$I_w=217 \times D_w^{-0.99} \text{ (} I_w\text{-}D_w \text{ threshold)}$$

The thresholds derived various types of rainfall intensities differed significantly between each other (Fig.3). The I_i - D_a threshold is the largest one of the three thresholds, and I_a - D_a model is the smallest.

When the data of rainfalls without causing debris flows are available, the threshold is defined as the best separator of the rainfall conditions that resulted and did not result in debris flows (Guzzetti, Peruccacci et al. 2007). To test the reliabilities of the various thresholds, we plot the data that the rainfall intensities are more than 10 mm/h during the three storms, but did not cause debris flows in the Fig. 3a. The reason for the application of 10 mm is that 10 mm is used to delimit a rainfall event in the studied regions susceptible to debris flow, and the overland flow on the surface of a slope is generated before accumulative rainfall reached 10 mm (Ma et al. 2016). At the same time, the data of previous studies (Ma, Wang, Du, Wang and Li 2016, Wang 2020) are plotted into the Fig. 3a. These data include the peak and average intensities (Ma, Wang, Du, Wang and Li 2016, Wang 2020).

The rainfall threshold derived from instantaneous intensity show high ability in separating the rainfalls inducing from those without inducing debris flows. Almost all of the data without causing debris flows, particularly those with similar rainfall durations, fall into the safety region delimited by the I_i - D_a threshold (Fig. 3a). Furthermore, the instantaneous intensity of the debris flows occurred on 21-22 July, 1989 (Wu

2001) also fall into the risk region delimited by our I_i - D_a threshold (Fig.3a). In contrast, many data of the average intensities that did not result in debris flows fall into the risk region defined by the I_a - D_a threshold (Fig. 3a). Similar to the I_a - D_a threshold, the threshold derived from the intensity over the whole rainstorms also show a low ability in separating the rainfalls inducing from those without inducing debris flows. Most importantly, the I_w values of many rainfall storms, which caused debris, falls into the safety region of the I_w - D_w thresholds, indicating a low accurate. These data consistently suggest that the occurrences of the debris flows are closely related to the instantaneous intensities and antecedent durations of rainfall events, and thus the I_i - D_a threshold is more accurate than those derived from other two intensity types. In contrast, the I_a - D_a and I_w - D_w thresholds might underestimate the precipitation or intensity triggering debris flows, and thus have a high rate of false alarm. This conclusion is consistent with the coincidence of the debris flows to the high rainfall intensities identified in both the three and previous storms in Beijing. Of course, this postulation need further research in consideration of the limited spatial and temporal coverage of the three storms in this study.

Comparison with previous thresholds

The rainfall threshold as the lower boundary of rainfall conditions, permits a direct comparison of thresholds based on various intensity types, though the rainfall thresholds are derived from various intensities, (Aleotti 2004, Cannon, Gartner, Wilson, Bowers and Laber 2008, Dahal and Hasegawa 2008, Fausto, Silvia, Mauro and P. 2008, Guzzetti, Peruccacci, Rossi and Stark 2007, Saito, Nakayama and Matsuyama 2010). There are several studies on the I-D rainfall thresholds in Beijing mountain areas (Ma, Deng and Wang 2018, Ma, Wang, Du, Wang and Li 2016, Tu et al. 2017, Wang 2020). Among these studies, Ma et al. (2016) and Wang et al. (2020) made the most comprehensive studies (Ma, Wang, Du, Wang and Li 2016, Wang 2020). The study of Ma et al. (2016) established both regional and local I-D thresholds based on the data of 23 debris flows occurred during the interval from 1963 to 2012. They proposed different rainfall thresholds based on the debris flows occurred before and after 2000. The minimum thresholds for the thresholds are $I=31.2 \times D^{-0.3}$ and $I=32 \times D^{-0.2}$. Wang (2020) established a rainfall thresholds ($I=56.9 \times D^{-0.746}$) based on 49 events occurred from 1949 to 2012. In addition, Tu and Ma (2017) also established a threshold during various time periods using peak intensities of 18 events from 1989 to 2012. All these threshold are plotted into the Fig.3b. In addition, the data of the rainstorms inducing debris flows from 1949 to 2012 are also added in this Fig.3b

Fig.3b shows that the I_i - D_a threshold is higher than other thresholds in Beijing, indicating a significant difference of the instantaneous threshold from those based on other intensities. The I_a - D_a threshold is very similar to that derived from the storm data from 1949 to 2012. All of the storm data from 1949 to 2012, which induced debris flows, fall into the risk region delimited by I_a - D_a threshold derived from the three storms. These characteristics indicate that the pattern of the storms inducing debris flows did not change significantly in the studied region, and the I_a - D_a of this study can well define rainfall conditions resulting in debris flows. The local threshold for Fangshan region proposed by Ma et al. (2016) is the smallest one of all the thresholds in Beijing, but it show no significant difference from that of Wang

(2020), particularly, when the rainfall duration exceed 6 hours (Fig.3b). The I_a - D_a threshold in this study, together with the threshold of Wang (2020) and local thresholds of Ma et al. (2016), can well define the average rainfall condition that resulted in debris flows, whereas they might have a high rate of nuisance alarms as pointed above.

Implication for the dynamics of debris flow in Beijing

The data of this study suggest that the rainfall intensity should play a dominant role in triggering the debris flows in the mountain areas of Beijing. As discussed above, all the debris flows in Beijing occurred during the interval with high intensity. Another obvious characteristics is that the high intensive rainfall sustained at least two hours before the debris occurred (Fig. 2). The serious disasters occurred in the regions where the long-term high intensive storms occurred. The most serious disasters occurred in Hebeizhen and Xiayunling areas during the storm on 21 July, 2012. In both sites, the heavy rainfall lasted about 3 hours before triggering a debris flow. The rainfall intensities from 9 to 11 hours are 65, 84, and 92 mm/h in Hebeizhen (Fig. 2), reaching the level of a 500-year storm. Similarly, the debris flows in Xiayunling were caused by 3-hour storm with an intensity of >48.5 mm/h, reaching the level of a 100-year storm. All these evidences suggest that the high intensive, continuous rainfall might play a dominant role in triggering debris flows in Beijing.

However, rainfall intensity cannot interpret the debris flows in Beijing alone. The cumulative precipitation from the beginning of the rainfall to the occurrence of debris flows may also play a substantial role. In many sites, the occurrences of the debris flows do not always correspond to the maximum rainfall intensity. Only when both accumulative rainfall and intensity reach a threshold could the debris flows be triggered (Fig. 2). During the storm on 21 July, 2012, no debris flows occurred when the cumulative precipitations were relative small in Mentougou (118.4 mm) and Longquan sites (84.3 mm), despite the rainfall intensity reached the maximum (Fig.2). Only when the cumulative rainfall reached 187.4 and 203.9 mm (3-4 hours delay to the maximum intensity) did the debris flows occurred (Fig. 2a). Similarly, the rainstorms with high intensity and low precipitations during the storm on 16 July, 2018 also caused few debris flows (Fig. 2). The intensities on the site of Bangheyan, Xiwanzi, and Yunmengshan are higher than 55 mm/h, but the corresponding cumulative precipitations are small. No debris flows or landslides occurred in these regions, though serious floods occurred. These evidences indicate that neither the rainfall intensity nor cumulative rainfall can interpret the debris flows in Beijing alone. Only when both rainfall intensity and cumulative rainfall reach a threshold simultaneously do debris flows occur. This postulation has been proved by the evidences across the globe covering various climate zones (Fausto, Silvia, Mauro and P. 2008), including central and southern Europe (Guzzetti, Peruccacci, Rossi and Stark 2007), Japan (Saito, Nakayama and Matsuyama 2010), America (Baum and Godt 2010), and the areas with high gradient slope in Himalaya mountains (Dahal and Hasegawa 2008) and Taiwan Island (Chien-Yuan et al. 2005).

Above evidences indicate that the debris flows in Beijing are triggered by the combination of high intensive rainstorm with high cumulative precipitation. This provides some deep insights into the

dynamics of debris flows in Beijing. It is well known that high intensive rainstorms must lead to flood occurrences, but mustn't result in debris flows. This is related to the underlying forcing of flood and debris flows. Debris flows are distinguished from floods in major forcing. The debris flow is that masses of poorly sorted sediments agitated and saturated with water, surge down slopes in response to gravitational attraction (Iverson 1997). As pointed by Iverson (1997), there are three factors for the development of debris flows: 1) failures of debris masses, 2) enough water to saturate the mass, and 3) sufficient conversion of gravitational potential energy to internal kinetic energy to change the style of motion that can be recognized as flow. The three factors must be satisfied almost simultaneously for debris flow occurrences (Anderson and Sitar 1995, Ellen and Fleming 1987, Iverson 1997). For the debris flows in Beijing, the long-term rainfall and its resultant high cumulative rainfall before debris flow occurrences provide enough time for water infiltrating and saturating debris sediments, mobilizing sediments by increasing the pore pressures of the sediments. Simultaneously, the high water flows and surges caused by intensive storms incorporate and retain the mobilized sediments, flowing down the slope and forming debris flows.

Conclusion

This paper made a systematic analysis on the evolution of recent three rainstorms and their association with the occurrence of debris flows in Beijing. The rainfall durations before the occurrences of debris flow are relative long, ranging from 5 to 15 hours. The debris flows occurred during the intervals with high rainfall intensity, whereas don't always correspond to the maximum of rainfall intensities, some of which are 3-4 hours delay to the maximum rainfall intensity. All of the debris flows occurred under the condition when both the intensities and cumulative precipitations reached a certain level, indicating a concerted work of rainfall intensity and cumulative precipitations.

The rainfall thresholds are estimated by various types of rainfall intensity, and the differences among them have been compared. The thresholds derived from the instantaneous intensity (I_t-D_a) display a high ability in separating the storms inducing from those without inducing debris flows. In contrast, the I_a-D_a and I_w-D_w thresholds show a low discriminating ability and thus high rate of false alarm, though the I_a-D_a model might be a high safe threshold indicated by its low value. These evidences demonstrate a significant role of instantaneous rainfall density in triggering debris flows, and a necessary of using instantaneous rainfall intensity and in situ monitoring in accurately estimating rainfall thresholds in future works.

Declarations

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Figures

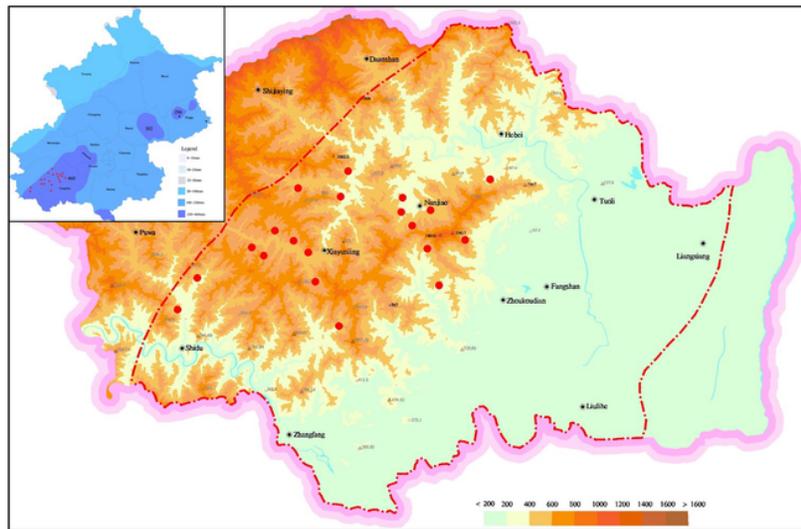


Fig. 1. The observed cumulative precipitations of the rain storm on 21 July, 2012 in Beijing, and the locations of debris flows. The dashed red line indicates the rainfall center.

Figure 1

The observed cumulative precipitations of the rain storm on 21 July, 2012 in Beijing, and the locations of debris flows. The dashed red line indicates the rainfall center. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

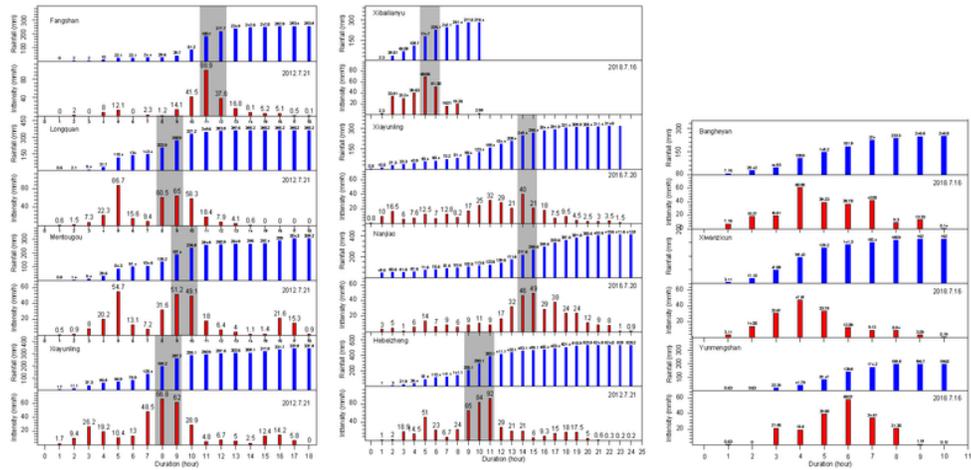


Fig. 2. The changes of rainfall intensity and cumulative precipitations in the sites where the debris flows occurred during the storms on 21 July, 2012(a), 20 July, 2016 (b), 16 July, 2018 (c). The shadow regions indicate the time of debris flows occurrence.

Figure 2

The changes of rainfall intensity and cumulative precipitations in the sites where the debris flows occurred during the storms on 21 July, 2012(a), 20 July, 2016 (b), 16 July, 2018 (c). The shadow regions indicate the time of debris flows occurrence.

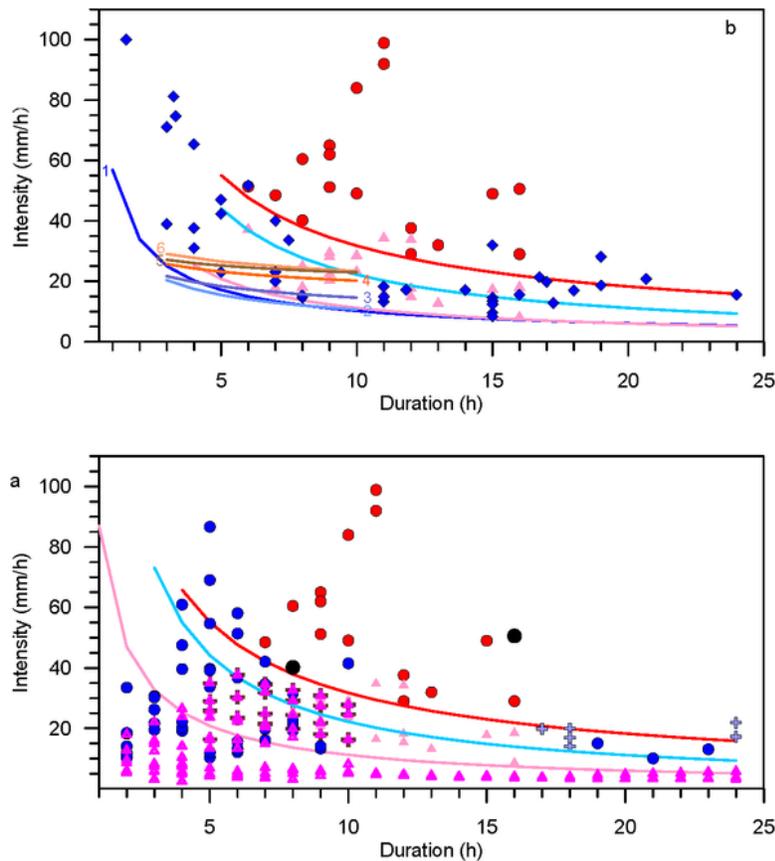


Fig. 3. Rainfall thresholds derived from instantaneous intensity (red line), average over the periods from the beginning of the rainfall to the occurrence of debris flows (pink line), and, the average intensity over the whole storm (blue lines) (a), and comparison with previous rainfall thresholds (b) (1 from Wang, 2020, 6 from Tu et al., 2, 3, 4, 5 are regional (4 derived from the data after 2000), and local thresholds of Fangshan (2) and Miyun (5) from Ma et al., 2016). Red and blue solid cycles are the instantaneous intensities inducing and without inducing debris flows, respectively, and the large black cycles are data of the instantaneous intensity of the storm in 1989 (Wu et al., 2001); Triangles are the average intensities before occurrences of debris flows (Pink solid), and the average intensities with cumulative precipitation larger than 10 mm but without causing debris flows (Magenta hollow); The crosses are the average intensities over whole storms inducing (pastel blue) and without inducing debris flows (dark brown). The blue rhombus is the data of the average intensities of the rainfalls triggering debris flows from 1949 to 2011(from Wang, 2020).

Figure 3

Rainfall thresholds derived from instantaneous intensity (red line), average over the periods from the beginning of the rainfall to the occurrence of debris flows (pink line), and, the average intensity over the whole storm (blue lines) (a), and comparison with previous rainfall thresholds (b) (1 from Wang, 2020, 6 from Tu et al., 2, 3, 4, 5 are regional (3, 4 derived from the data after 2000), and local thresholds of Fangshan (2) and Miyun (5) from Ma et al., 2016). Red and blue solid cycles are the instantaneous

intensities inducing and without inducing debris flows, respectively, and the large black cycles are data of the instantaneous intensity of the storm in 1989 (Wu et al., 2001); Triangles are the average intensities before occurrences of debris flows (Pink solid), and the average intensities with cumulative precipitation larger than 10 mm but without causing debris flows (Magenta hollow); The crosses are the average intensities over whole storms inducing (pastel blue) and without inducing debris flows (dark brown). The blue rhombus is the data of the average intensities of the rainfalls triggering debris flow from 1949 to 2011(from Wang, 2020).