Characteristics of rainfall and runoff in different extreme precipitation events in the Beijing mountain area

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ABSTRACT

This study was based on a rainstorm that happened in Beijing on 20 July 2016. We analyzed the characteristics of rainfall and runoff during this rainstorm, compared it to rainstorm 721, and investigated why no surface runoff was observed during this rainstorm. A runoff plot experiment showed that almost all runoff consisted of deep interflow (40–60 cm). For runoff plots with identical vegetation, the slope was smaller, and the lag time of the deep interflow relative to the process of rainfall was shorter. The runoff yield of the deep interflow was inversely proportional to the slope. Compared to plots with pure tree forest and shrub forest, the interflow process curve of plots with coniferous and broad-leaved mixed forest was relatively gentle during the rainfall process. Thick litter layers, low antecedent moisture content of the soil, high gravel content of the soil, and the short duration of high intensity rainfall are the causes for the observed lack of surface runoff. To simultaneously prevent flooding and waterlogging, we propose to utilize vegetation to improve water storage at the reservoirs and to replenish the groundwater during cumulative rainstorms with a stable rain tendency.

Key words | deep interflow, rainfall intensity, rainstorm, runoff plots, surface runoff, vegetation

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INTRODUCTION

Runoff formation is affected by rainfall, vegetation, soil, and other factors (Kosmas *et al.* 1997; Castillo *et al.* 2003; Pan & Shangguan 2006). The rainfall factors include moisture and intensity. In general, the stronger the rainfall and the more abundant the runoff during the same rainfall, the greater the intensity of rainfall and the greater the likelihood for the production of surface runoff (Pruski & Nearing 2002; Liu *et al.* 2014). Vegetation both blocks and delays the occurring surface runoff by increasing surface roughness and the interception of litter for rainfall can effectively delay the generation of surface runoff. The antecedent soil moisture content and soil porosity are also important factors that influence the formation of runoff. Litter can be combined with the root system of the vegetation to improve soil physical and chemical properties, increase soil infiltration, and thus reduce surface runoff (Sala *et al.* 1990; Hart & Frasier 2003; Zhang & Cong 2014).

Interflow is an important part of the water budget of rivers and an important supply for groundwater, rivers, and lakes. Interflow is also a central element of the hydrological cycle (Wilson *et al.* 2008). In recent years, a large number of studies has been conducted at home and abroad that investigated the characteristics and influencing factors of interflow (Pei *et al.* 2006; Liu 2011; Dusek *et al.* 2012). At present, the research methods mainly include runoff plot experimental methods, geophysical methods, model simulation methods, and tracer methods. Rainfall intensity impacts the interflow under different land use

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patterns at different degrees, and artificial rainfall simulation experiments have shown the vegetation cover rate to be directly proportional to the runoff yield of interflow (Xu *et al.* 2010). Gravel on the surface has been reported to increase the runoff yield of interflow (Wang *et al.* 2012a, 2012b). The thickness of the soil layer significantly impacts the interflow production mechanism as determined by artificial rainfall simulation experiments (Fu *et al.* 2011). Interflow generally occurs in response to heavy rain and the interflow duration is independent of rainfall intensity after the precipitation process (Liu *et al.* 2002). According to statistical studies and despite the decreasing rainfall since 1951 in Beijing, extreme precipitation events, such as rainstorm, are on the rise. In recent years, a typical extreme precipitation event was rainstorm 721 in Beijing in 2012. These rainstorms caused severe waterlogging in the city, had a severe impact on urban traffic, and caused severe economic losses and casualties. Due to global warming, water cycle changes, increased atmospheric instability, the intensity and frequency of heavy rainfall and other disasters are increasing, and extreme weather events will not be concentrated in one area but will be randomly distributed all over the world.

A large body of research has been conducted on the runoff processes on slopes in response to rainstorms; however, most of these studies focused on the process and the characteristics of surface runoff. Much research has been conducted on the interflow, mainly through artificial rainfall; however, very little research has been conducted on the characteristics of interflow on slopes in response to rainstorms. This study analyzed the process and characteristics of the resulting interflow, and analyzed and discussed the underlying reason for the lack of slope surface runoff under the extreme precipitation condition that was associated with the rainstorm on 20 July 2016 in Beijing. With this study, we hope to provide a theoretical basis for the study of runoff characteristics as well as disaster prevention and control for heavy rainfall in this region.

STUDY AREA

The experimental station is located in the Beijing Jiufeng National Forest Park (116°05′45″E, 40°03′46″N) (Figure 1). The region has a semi-humid continental climate with an average annual temperature near 11 °C, an average annual precipitation of 600 mm, an average annual evaporation between 1,800 and 2,000 mm, and a frost-free period of approximately 150 days. The soil type is cinnamon soil, and the average soil thickness ranges between approximately 60 and 70 cm. The typical vegetation types in this region are deciduous broad-leaved forests and coniferous and broad-leaved mixed forests, with species such as *Pinus tabulaeformis*, *Platycladus orientalis*, and *Quercus variabilis*. Due to geographical factors and the role of the monsoon, precipitation in summer accounts for more than 85% of the total precipitation of this region, and the frequency of rainstorms' occurrence in summer is very high.

METHODS AND DATA

In this study, we established five long-term observation sites at different altitudes and different stand types where we investigated the main dominant tree species in the forest, from which selected tree species and site conditions were typical and representative for the Beijing mountain area. Five runoff plots were established on the slope of each site, and the sizes of all five plots were identical, with an area of 100 m^2. Each runoff plot had four sets of water outlets and water tanks, which collect surface runoff and interflow. The depths of the outlets for interflow were 0–20 cm, 20–40 cm, and 40–60 cm (Figure 2). Table 1 lists the basic information of all five runoff plots.

RESULTS AND DISCUSSION

Dynamic rainfall characteristics

An event is referred to as a rainstorm when the precipitation is above 50 mm during 24 h. Precipitation above 250 mm during 24 h is defined as an extraordinary rainstorm. According to the meteorological station data of the Jiufeng National Forest Park, the investigated rainstorm began at 8:30 on 19 July 2016, ended at 23:00 on 20 July, and lasted 38.5 h with a cumulative rainfall of 395.1 mm.

This rainstorm caused the largest accumulated rainfall since rainstorm 721 in Beijing in 2012. The rainstorm

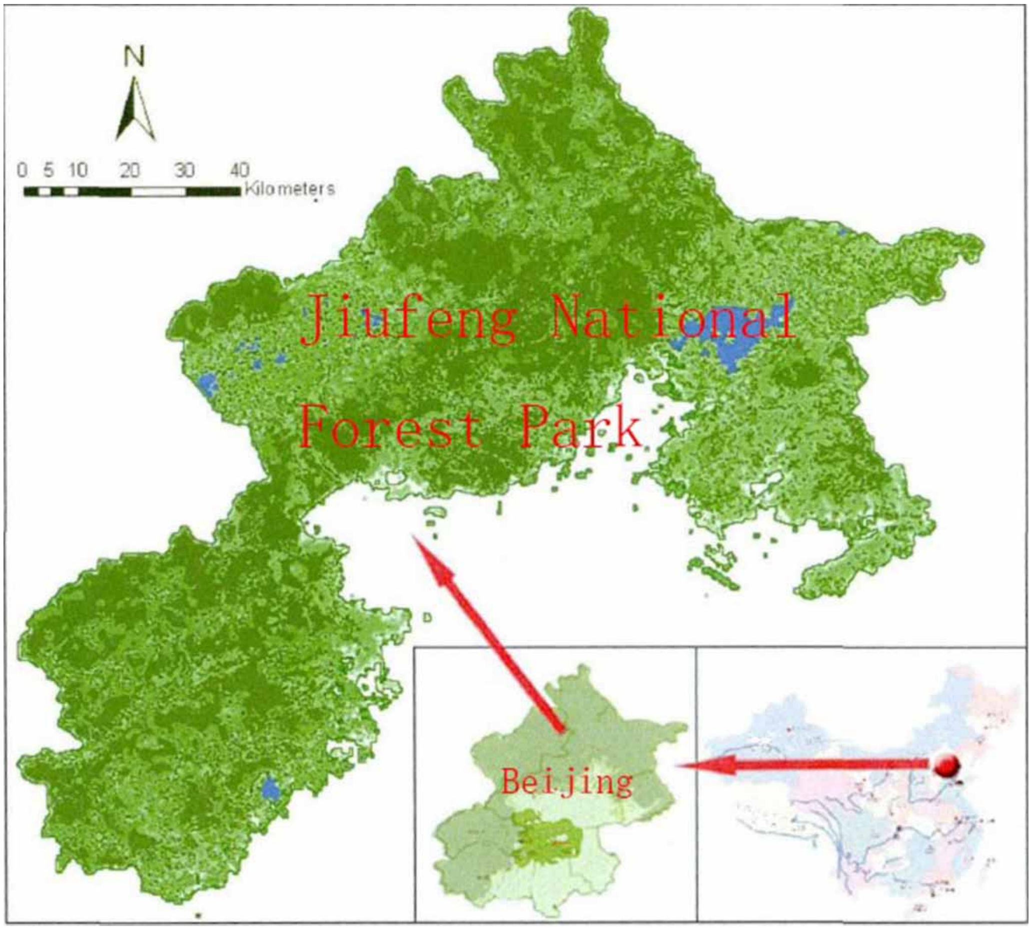

Figure 1 | Location map for the study area.

investigated here had a larger area, larger average rainfall, and longer duration than rainstorm 721. Rainstorm 721 began at 11:43 on 21 July 2012, ended at 02:43 on 22 July, and lasted for 15 h with a cumulative rainfall of 146.8 mm.

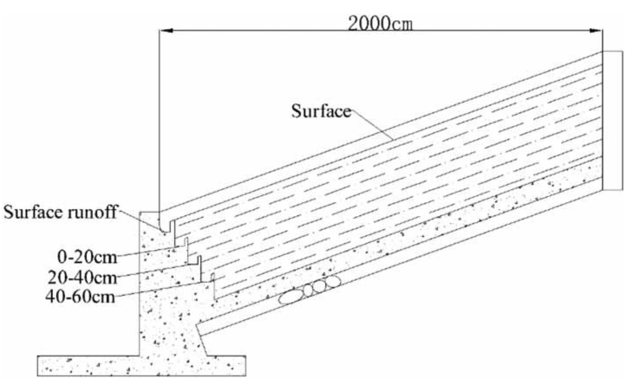

Figure 2 | Profile of the runoff plot.

As shown in Figure 3, the rainstorm reached a maximum rainfall intensity of 38.8 mm/h, at 13:00 on 20 July, and the average rainfall intensity was 13.6 mm/h. The rainfall process curve follows a single peak curve, and the peak value appears during the middle of the rainfall process.

There were discontinuities in the rainstorm until 8:30 on 20 July. The precipitation between 10:00 and 19:00 on 20 July accounted for 82% of the total precipitation. During this period the average rainfall intensity was 28.5 mm/h, after which the rainfall intensity gradually weakened until the end.

Analysis of the runoff producing process

The runoff yield of No. 1 (*Platycladus orientalis*) runoff plot was 2,848.4 L, which was the highest of the five runoff plots

Table 1 | Basic information of the five runoff plots

Runoff plot	Latitude and longitude	Altitude (m)	Dominant tree	Main shrub	Slope (m)	Litter thickness (cm)
No. 1	40°3.766′N 116°5.750′E	145	*Platycladus orientalis*	*Vitex negundo* and *Grewia biloba*	20	3.8
No. 2	40°3.694′N 116°5.609′E	155	*Pinus tabulaeformis*	*Vitex negundo* and *Grewia biloba*	25	4.1
No. 3	40°3.638′N 116°5.482′E	155	Shrubs	*Vitex negundo*	30	2.3
No. 4	40°3.508′N 116°5.354′E	450	*Pinus tabulaeformis*	*Vitex negundo* and *Grewia biloba*	20	4.5
No. 5	40°3.511′N 116°5.242′E	450	*Pinus tabulaeformis* and *Quercus variabilis*	*Vitex negundo* and *Myripnois dioica*	25	7.8

in this rainstorm process, followed by No. 4 (*Pinus tabulaeformis*) and No. 5 (*Pinus tabulaeformis* and *Quercus variabilis*), in which the runoff yield was 2,047.7 L and 1,882.8 L, respectively. The runoff yield of No. 2 (*Pinus tabulaeformis*) was 1,265.3 L, and No. 3 (shrubs) was the smallest, with a runoff yield of 135.6 L.

In all five runoff plots, the surface and the first layer (0–20 cm) of interflow did not have any runoff, the second layer (20–40 cm) of interflow had a small amount of runoff, while almost all the runoff occurred in the third layer of interflow (40–60 cm). The runoff yield distribution of each plot is shown in Figure 4. The surface and the first layer (0–20 cm) of the interflow showed no runoff; therefore it is not represented on the graph. Prior to 13:27 on 20 July, with the exception of No. 4 runoff plot, there was no runoff in any of the other runoff plots. The time of occurrence of runoff in runoff plot No. 4 was 11:04 on 20 July. The runoff peak value of the five runoff plots occurred at 17:00 on 20 July: the peak value of No. 1 runoff plot reached 635 L/h, the peak value of No. 2 runoff plot reached 333 L/h, and the peak value of No. 3 runoff field was the smallest with 34 L/h. The end times of No. 1 to No. 4 runoff plots were very close; however, the runoff of No. 5 runoff plot lasted until 18:00 on 21 July. The start and stop times of the runoff for the five runoff plots are shown in Table 2.

Analysis of the time of interflow

Neither the surface nor the first layer of interflow showed any runoff. Almost all of the runoff occurred within the third layer of interflow; therefore, it was necessary to compare and analyze the process and characteristics of deep interflow (40–60 cm) of all five runoff plots, which are situated in different vegetation zones. As shown in Figure 5,

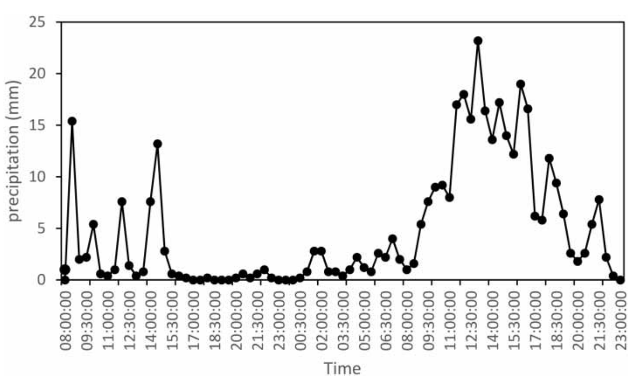

Figure 3 | Rainfall during the July 2016 storm event.

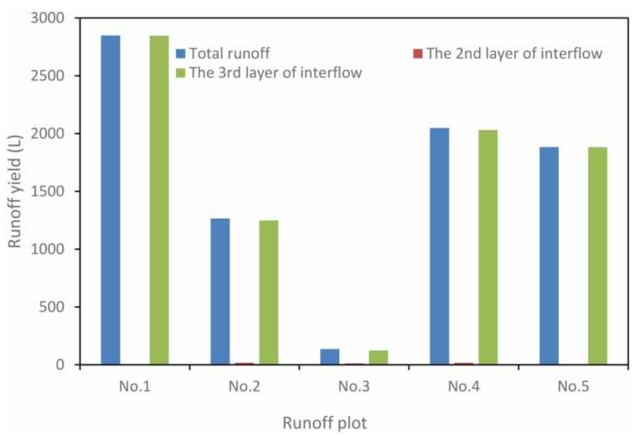

Figure 4 | Runoff yield distribution of each plot.

Table 2 | Start and stop times of the runoff

Time of runoff	No. 1	No. 2	No. 3	No. 4	No. 5
Start (20 July)	13:27	13:35	13:51	11:04	13:50
End (21 July)	2:15	2:18	2:23	2:50	18:00

the curves of the interflow process (40–60 cm) in runoff plots No. 1 to No. 4 are similar; however, the curve of runoff plot No. 5 was gentler than those of the other four plots. The interflow process lagged behind the rainfall process, and the lag times were different in all five runoff plots. Runoff plot No. 4 began to generate interflow at 11:04 on 20 July and its delay behind the rainfall start time was 26 h. Its lag time was the shortest of the five runoff plots, but the lag times of the other four runoff plots were similar: The lag time of runoff plot No. 1 was 28 h 58 min, the lag time of runoff plot No. 2 was 29 h 06 min, the lag time of runoff plot No. 3 was 29 h 32 min, and the lag time of runoff plot No. 5 was 29 h 31 min. The lag time of runoff plot No. 4 was 2 h 45 min ahead of these of the other four plots. Table 1 shows that the dominant tree species of runoff plots No. 4 and No. 2 was *Pinus tabulaeformis,* and the main shrubs were *Vitex negundo* and *Grewia biloba*. We considered the vegetation and soil conditions of both runoff plots to be basically identical; therefore, the main site factor that caused the difference in the starting time of the interflow in both plots under the same rainfall conditions should be a slope. In this study, the slope of runoff plot No. 2 was 20°, and the slope of runoff plot No. 4 was 25°. This indicates that under identical vegetation conditions, the smaller slope had an earlier starting time of the observed deep interflow in this precipitation event. However, the linear fit between the slope and the lag time of the deep interflow was not obvious, and the quality of fit of the polynomial was good (Figure 6).

The peak time of the interflow for the five runoff plots had a certain lag relative to the peak time of the rainfall, which may indicate that rainfall was not the sole determinant of the interflow-producing process; a conclusion that is consistent with the findings of Yin *et al.* (2006). Their research showed that the interflow duration was mainly affected by a single factor. The interaction effect of various factors was weak, the interflow duration of the surface and the bottom layer differed, and the relevance of the interflow duration of the bottom layer and rainfall intensity were good; however, the relevance of surface layer and rainfall intensity to interflow duration were poor (Yin *et al.* 2006). The peak times of interflow of runoff plots No. 1 to No. 4 were almost identical. Compared to the other four runoff plots, the peak time of interflow of runoff plot No. 5 was smallest, and the end time of interflow of runoff plot No. 5 happened significantly later than the average time of the other four runoff plots (almost 16 h). The interflow process curve was relatively gentle over the whole rainfall process. This was mainly because the vegetation type of runoff plot No. 5 was a mixed coniferous and broad-leaved forest,

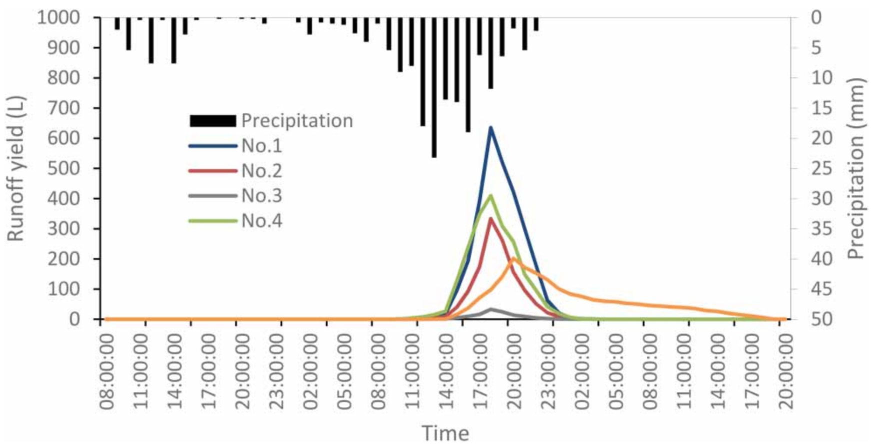

Figure 5 | Process of deep interflow.

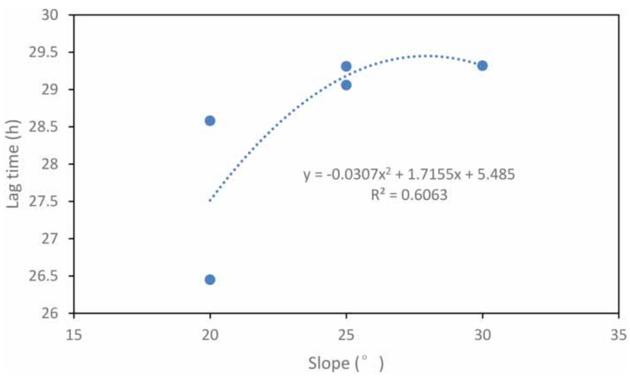

Figure 6 | Fitting curve of lag time and slope.

with a strong interception of canopy and litter, and greatly changed physical and chemical properties of the soil by both litter and roots. This may indicate that mixed coniferous and broad-leaved forests can more effectively inhibit interflow generation, and delay the interflow peak value compared to pure tree forests and shrub forests.

Analysis of interflow runoff yield

The cumulative runoff yield of the interflow in the runoff plots ranged from large to small: No. 1 (2,848.4 L) > No. 4 (2,047.7 L) > No. 5 (1,882.8 L) > No. 2 (1,265.3 L) > No. 3 (1,35.6 L). All the rainfall infiltrated into the soil of the five runoff plots under the rainstorm condition. Figure 7 and Table 1 show that the relationships between cumulative interflow and slope in the five runoff plots under this rainstorm condition were all in accord with this law: the slope was smaller, and the cumulative deep interflow was larger. We found that linear fitting between the cumulative deep interflow and the slope was good in all five runoff plots; the goodness of fit was 0.854, which showed a good negative correlation (Figure 8). Previous research showed that, under identical rainfall conditions, the runoff yield of interflow is proportional to the slope (Ding *et al.* 2008), which is contrary to the conclusions found in this study. In addition to the factors of soil and vegetation, the reason for this phenomenon is that this study was based on a rainstorm representing an extreme weather condition, and there was no surface runoff; however, almost all of the runoff occurred as deep interflow throughout the five plots.

During rainstorm 721, the total runoff yield of runoff plot No. 3 was 130 L, which was the largest in the five runoff plots in this rainstorm process, followed by runoff plots No. 1 and No. 5, in which the runoff yields were 85 L and 68 L, respectively. The runoff yield of No. 2 was the smallest, with a runoff yield of 37 L. In terms of surface runoff, the runoff yield of runoff plot No. 3 was 121 L, which was the largest in the five runoff plots during this rainstorm process, followed by runoff plots No. 1 and No. 4, in which the runoff yields were 84 L and 26 L, respectively. The runoff yield of runoff plot No. 5 was the smallest, with a runoff yield of 7 L. In terms of interflow, the runoff yield of the runoff plot No. 5 was 61 L, which was the largest in the five runoff plots in this rainstorm process, followed by runoff plots No. 4 and No. 3, in which the runoff yields

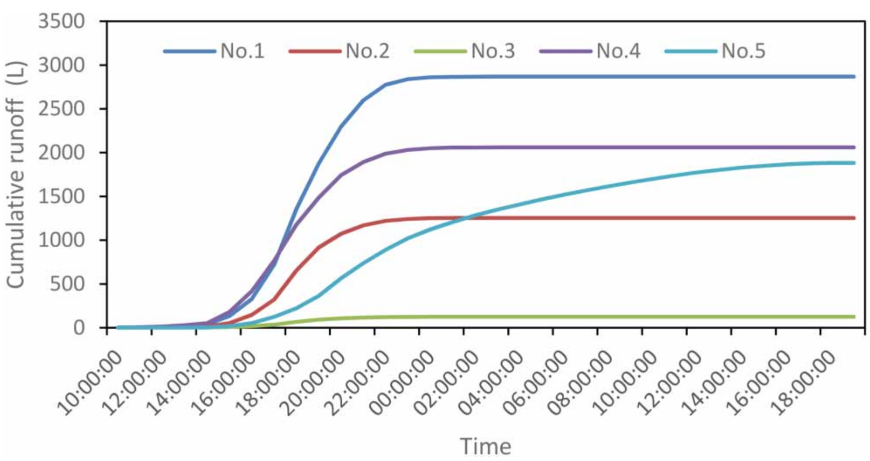

Figure 7 | Cumulative runoff.

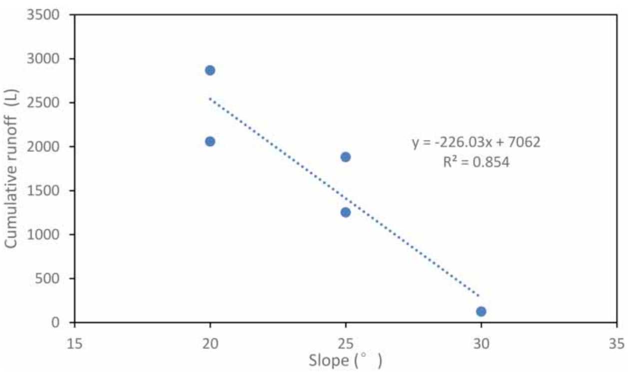

Figure 8 | Fitting curve of cumulative runoff and slope.

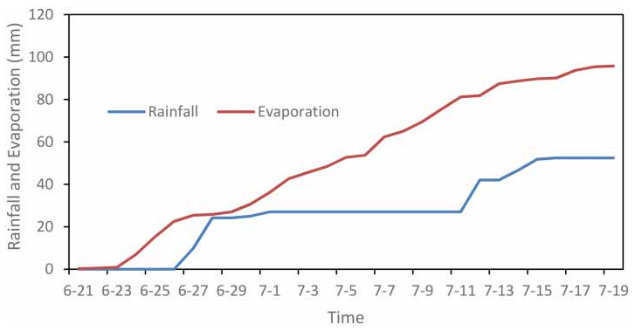

Figure 9 | Cumulative rainfall and cumulative evaporation one month before the rainstorm.

were 11 L and 9 L, respectively. The runoff yield of No. 1 was the smallest, with a runoff yield of 1 L. We analyzed the runoff characteristics of rainstorms 720 and 721 under different vegetation conditions, and found that there was no surface runoff in five runoff plots in rainstorm 720, while for the latter was just the opposite; it was the biggest difference of runoff characteristics between two extreme precipitation events.

Analysis of reasons for the lack of surface runoff generation

Antecedent moisture content of the soil

Through observational data from the meteorological station, we obtained cumulative rainfall and cumulative evaporation data for this area for one month before the rainstorm. We found that the precipitation for the two time periods of 21 June to 26 June and 2 July to 10 July were 0; however, the cumulative evaporation was always on the rise and the cumulative evaporation was higher than the accumulated rainfall for this month (Figure 9). We monitored the moisture content of soil via Em50, which is a five-channel data collector produced by the METER company, and can be used to measure soil water potential, conductivity, moisture, and temperature in different soil layers. We found that the moisture contents of soil in each layer prior to the rainstorm were very low. The moisture content of soil in the second (20–40 cm) and third (40–60 cm) layers remained almost unchanged 1 week prior to the rainstorm; however, the surface layer (0–20 cm) had a descending trend during this month (Table 3). The cumulative infiltration was higher under the lower antecedent moisture content of the soil, and low antecedent moisture content of soil has been shown to delay the generation of surface runoff (Wang *et al.* 2008; Chifflard *et al.* 2009; Liu *et al.* 2011).

Vegetation

The transpiration of vegetation can reduce surface water, and vegetation can increase the opportunity for the evaporation of surface runoff due to its effect of blocking and delaying surface runoff. In addition, the vegetation litter layer can intercept part of the precipitation. Several experiments under simulated rainfall events have shown that surface cover resulted in a good effect of reducing flow (Keesstra *et al.* 2016; Prosdocimi *et al.* 2016a, 2016b), and a large body of research has shown that, compared to bare slopes, the surface runoff of a slope with litter is significantly

Table 3 | Antecedent moisture content of soil

	Soil moisture content (%)		
Date	1st layer (0–20 cm)	2nd layer (20–40 cm)	3rd layer (40–60 cm)
12 July	11.2	7.8	7.2
13 July	10.9	7.8	7.3
14 July	10.8	7.8	7.2
15 July	10.1	7.9	7.3
16 July	9.9	8	7.2
17 July	9.8	7.9	7.3
18 July	9.4	7.8	7.3
19 July	16.5	17.3	7.7

decreased (Jin *et al.* 2014; Liu *et al.* 2017). In this study, the average thickness of the litter layer was 4.5 cm, and the delaying effect surface runoff generation by the litter was substantial. Surface cover can also effectively stop water loss in agriculture, e.g., delaying ponding and runoff generation in vineyards and persimmon plantations (Prosdocimi *et al.* 2016a, 2016b; Cerdà *et al.* 2016).

Gravel

Through a previous field sample survey, we found that the content of soil gravel (calculated according to the volume ratio) was relatively high in this area. The average content of gravel or debris with particle sizes above 2 mm in soil was more than 50% while the maximum reached 85%. The high content of gravel was beneficial for the infiltration of rainfall. A cover of rock fragments delayed surface runoff and increased infiltration and subsurface runoff (Wang *et al.* 2012a, 2012b).

Intensity and timing of rainfall

Surface runoff can be generated in two ways: (1) runoff formation at natural storage and (2) runoff formation in excess of infiltration. Runoff formation in excess of infiltration is generated as a response of high intensity rainfall, occurring during a short period of time and because the rainfall exceeds the infiltration. Runoff formation at the natural storage was generated because the rainfall duration was long, and the soil reached saturation under the condition of high precipitation. Surface runoff was generated as the rainfall continued, while at the same time, interflow and shallow groundwater also began to generate. From the beginning of the rainfall to 8:30 on 20 July, there was a discontinuity in the rainstorm process, where the duration of rainfall was long, while rainfall during this period accounted for only 15% of the total rainfall. Additionally, the antecedent moisture content of the soil was low; therefore, it did not reach the condition of runoff formation at the natural storage. The precipitation that occurred from 10:00 to 19:00 on 20 July accounted for 82% of the total precipitation; however, the duration of heavy rainfall was short, and the high content of gravel contributed to the rainfall infiltration. The precipitation during that short period of time did not exceed the amount of soil infiltration, and all runoff was generated as a form of interflow. Thus, there was no runoff formation in excess of infiltration. Rainstorm 720 had larger accumulated rainfall (395.1 mm) and smaller maximum rainfall intensity (38.8 mm/h) than rainstorm 721, with a maximum rainfall intensity of 103.8 mm/h. We suggest that such cumulative rainstorms with stable rain tendency are the most important reason for the lack of surface runoff. The runoff plots only collected interflow during the rainstorm event and there was no surface runoff in the five plots. A qualitative analysis of several factors related to vegetation, rainfall, and soil showed the cause for the lack of surface runoff to be associated with the rainstorm. However, no quantitative relationship was established and, therefore, the underlying reasons for the lack of no surface runoff generation require further exploration.

This rainstorm was a continuous rainfall caused by vapor rising in response to a topographic effect. Although the total rainfall was enormous, the rain tendency was stable. This may be one of the signs of an abundant water period re-emerging in northern China. Utilization of these stable, gentle rainstorms would be very beneficial to improve water storage of the reservoirs and for replenishing the groundwater. However, the existence of vegetation is conducive for the increase of infiltration, to block surface runoff, to maximally use rainfall to replenish groundwater, and to prevent the occurrence of floods and waterlogging in such rainstorm types. Related data showed that the Beijing plain groundwater level increased by 0.79 m, the city's groundwater reserves increased by 400 million m^3, and the city's average soil moisture content increased significantly in response to this rainstorm. This is also conducive to the growth of plants.

CONCLUSIONS

In this study, we analyzed the characteristics of rainfall and runoff in a recent rainstorm and compared it to rainstorm 721. Furthermore, we analyzed the process and characteristics of deep interflow with different vegetation types, and we discussed the reason for the lack of no surface runoff under rainstorm conditions by observing runoff plots. We found that almost all of the runoff occurred as deep interflow. (1) Under the rainstorm conditions, when the runoff plots had identical vegetation, the runoff yield of deep interflow was inversely proportional to the slope; the smaller the slope, the earlier the start of deep interflow and the shorter the time delay of deep interflow relative to the onset of rainfall. (2) Coniferous and broad-leaved mixed forest can inhibit the generation of interflow more effectively and delay the interflow peak value compared to pure tree forests and shrub forests. (3) Rainfall is not the sole determinant of the interflow-producing process. (4) Through this comprehensive analysis, we found that the five runoff plots all have thick litter layers, which have the apparent effect of blocking surface runoff; the antecedent moisture content of the soil was low, the soil had high gravel content, and the duration of high intensity rainfall was short. These factors led to insufficient conditions of runoff formation at natural storage and runoff formation in excess of infiltration. In the future, we suggest to consider maximizing the role of vegetation and utilizing such cumulative rainstorms with stable rain tendency to improve the water storage of reservoirs, to replenish the groundwater, and to prevent the occurrence of floods and waterlogging.

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