

Rainfall interception of typical ecosystems in the Heihe River Basin: Based on high temporal resolution soil moisture data

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Abstract: Rainfall interception is of great significance to the fully utilization of rainfall in water limited areas. Until now, studies on rainfall partitioning process of typical ecosystems in Heihe River Basin, one of the most important inland river basins in China, is still insufficient. In this study, six typical ecosystems were selected, namely alpine meadow, coniferous forest, mountain steppe, desert, cultivated crop, and riparian forest, in Heihe River Basin for investigation of the rainfall interception characteristics and their influencing factors, including rainfall amount, duration, and intensity, based on the gross rainfall and high temporal resolution soil moisture data obtained from 12 automatic observation sites. The results show that the average interception amount and average interception rate of the six ecosystems are significantly different: alpine meadow 6.2 mm and 45.9%, coniferous forest 7.4 mm and 69.1%, mountain steppe 3.5 mm and 37.3%, desert 3.5 mm and 57.2%, cultivated crop 4.5 mm and 69.1%, and riparian forest 2.6 mm and 66.7%, respectively. The rainfall amount, duration, and intensity all had impact on the process of rainfall interception. Among these three factors, the impact of rainfall amount was most significant. The responses of these ecosystems to the rainfall characteristics were also different. Analyzing rainfall interception with high temporal resolution soil moisture data is proved to be a feasible method and need further development in the future.

Keywords: rainfall interception; Heihe River Basin; soil moisture; rainfall utilization

1 Introduction

Rainfall interception is one of the most important hydrological processes, which affects the water balance at multi-scales (Llorens and Domingo, 2007). Rainfall changes its transportation route when it goes through the vegetation canopies, partitioning into interception,

Received: 2018-10-23 **Accepted:** 2019-03-16

Foundation: National Natural Science Foundation of China, No.91425301, No.91725000; State Key Laboratory of Land Surface Processes and Resource Ecology, No.2017-ZY-04

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throughfall, and stemflow, among which interception, further composed of two parts, evaporation and canopy water storage (Crockford and Richardson, 2000; Staelens *et al.*, 2008), causes a water loss from the vegetation (Loik *et al.*, 2004), throughfall leads to the spatial variability of the pattern of the rainfall that can reach the ground (Weltzin and Macpherson, 2000), and stemflow can reach deeper layers of the soil and increase the available water for the roots (Martinez-Meza and Whitford, 1996; Li *et al.*, 2009). In general, rainfall partitioning process leads to a significant redistribution of incident rainfall (Llorens and Domingo, 2007), and becomes an important part in the hydrology, especially in water limited regions.

Traditional rainfall interception experiments in shrub and forest ecosystems always set a series of collectors beneath the canopies to receive throughfall, fit collars around the entire circumference of the stem of the plants to collect stemflow, and calculate interception loss from the difference between the bulk rainfall and the sum of the throughfall and stemflow (Crockford and Richardson, 2000; Llorens and Domingo, 2007; Zhang *et al.*, 2015). Throughfall collectors need to be weighed and emptied after every rainfall event, make it difficult to realize automatic, real-time observation of rainfall interception process in a single rainfall event. A large number of self-recorded rainfall measuring devices are needed to achieve high temporal resolution of automatic observation, which is more expensive and difficult to manage. Moreover, most rainfall interception experiments focus on forest and shrub communities, whose method is not suitable for herbaceous plants because their height is much lower (Wohlfahrt *et al.*, 2006; Li *et al.*, 2009). Current methods often cause damage to the measured herbaceous plants (Monson *et al.*, 1992; Fan *et al.*, 2015). In recent years, with the development of automatic soil moisture measurement technology, high temporal resolution soil moisture data of multiple layers can be obtained (Bogena *et al.*, 2010). These data have been widely used to realize fine depiction of soil moisture dynamics (Liu *et al.*, 2015; Hu *et al.*, 2017; Wang *et al.*, 2017), and to analyze ecosystem evapotranspiration (Dekker *et al.*, 2007; Soubie *et al.*, 2016; Xu *et al.*, 2017). Based on the same principle of water balance, rainfall interception can also be depicted by the relationship between rainfall amount and soil moisture dynamic during the individual rainfall event. The increase in soil moisture content can be considered as the result of the infiltration of the throughfall and stemflow, while the difference between the bulk rainfall and the increase of soil moisture is mainly caused by the interception loss (Herbst *et al.*, 2008; Staelens *et al.*, 2008). This method can be an appropriate alternative of the traditional methods to achieve fine description of rainfall partitioning, and solve the problems that traditional experiments are difficult to achieve automatic and non-destructive observation of herbaceous communities (Yu *et al.*, 2012).

As China's second largest inland river, the Heihe River originates from the Qilian Mountains, and flows through Qinghai, Gansu, and Inner Mongolia provinces (Li *et al.*, 2001). Due to its great elevation gradient and different climate, the Heihe River Basin has a wide variety of unique ecosystems, consisting of alpine vegetation, oases, deserts, and riparian forest landscapes (Li *et al.*, 2013; Liu *et al.*, 2015; Fu and Pan, 2016). From the river's upper reaches in the south to the lower reaches in the north, multiple physiogeographic units of the Heihe River Basin make it ideal for studying soil moisture dynamics and rainfall partitioning on the basin scale (Wang *et al.*, 2009). Many studies on rainfall infiltration and partitioning

have been carried out in the Heihe River Basin so far (Tan *et al.*, 2009; Liu *et al.*, 2012; Yang *et al.*, 2012; Xu *et al.*, 2013; Peng *et al.*, 2014; Wan *et al.*, 2016). However, traditional methods are mostly used, with rare reports of rainfall partitioning based on high temporal resolution soil moisture data. In addition, these studies are basically carried out in the spruce forest and shrub ecosystems in the upper reaches (Xu *et al.*, 2013; Peng *et al.*, 2014; Wan *et al.*, 2016), with the lack of studies on alpine meadow, mountain steppe, and riparian forest ecosystems. In recent years, the synthetic research on the eco-hydrological process of the Heihe River Basin and the Heihe Watershed allied telemetry experimental research (Hi-WATER) experiment have built an integral observation system and data platform (Li *et al.*, 2013; Cheng *et al.*, 2014). The soil moisture observation network covers all the typical ecosystems in the basin and has achieved a large amount of automatic observation data of soil moisture, which make it possible to analyze the process of rainfall infiltration and partitioning. The specific objective of this study is to make out: (1) what are the similarities and differences of rainfall partitioning characteristics of different ecosystems in the Heihe River Basin; (2) which factors can influence the process of rainfall partitioning; and (3) whether high-resolution soil moisture data can be used to calculate rainfall interception.

2 Materials and methods

2.1 Study area

As the second largest inland river in China, the Heihe River is 821 km long with a drainage area of $1.429 \times 10^5 \text{ km}^2$. The river basin located in the arid and semi-arid region of northwest China, roughly between $37^\circ 44' - 42^\circ 40' \text{N}$ and $97^\circ 37' - 102^\circ 06' \text{E}$ (Figure 1). The upper reaches are located in the Qilian Mountains, on the northern margin of the Qinghai-Tibet Plateau with an elevation of more than 2000 m a.s.l. The climate in this region is characterized by large amount of precipitation, low temperature and evaporation, with regional mean annual temperature ranging from -5 to 4°C , mean annual precipitation of 250–500 mm, and annual evapotranspiration of 700–2000 mm. The middle reaches are flat, located at the east of the Hexi Corridor, with altitudes ranging from 1000–2000 m. Compared to the upper reaches, the climate of middle reaches is arid, with less precipitation, more evapotranspiration, and higher temperature. From the southwest to the northeast in this region, mean annual precipitation decreases from 200 mm to 55 mm, while the annual evapotranspiration increases from 1200 mm to 2200 mm. The lower reaches are located on the Alshan Plateau in the west of Inner Mongolia Plateau, with altitudes ranging from 980–1200 m. This area has less precipitation but stronger evaporation. The average annual precipitation is only 47.3 mm, while the average annual evaporation is as high as 2249 mm. The mean annual temperature is 8.2°C (Pan and Tian, 2011).

As can be seen from Figure 1, over 80% of the Heihe River Basin is covered by five ecosystems, namely, alpine meadow, coniferous forest, desert, mountain steppe, and cultivated crop. The riparian forest ecosystem, on the other hand, is a unique ecosystem developed in the inland river basin, and is of great significance for studying the eco-hydrological processes in this area. Therefore, these six ecosystems were selected as typical ecosystems in the Heihe River Basin (Table 1).

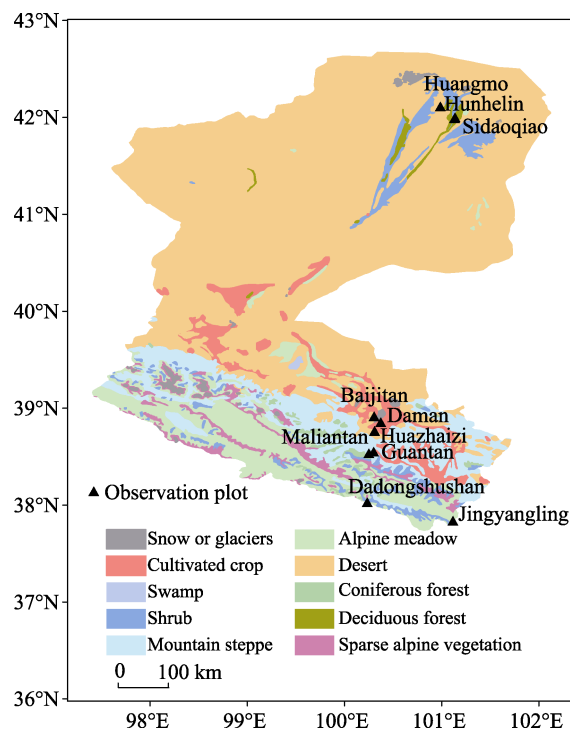


Figure 1 Ecosystem distribution and the field observation sites of the Heihe River Basin

Table 1 Stand characteristics and mean annual climate conditions of typical ecosystems

Ecosystems	Coverage (%)	Canopy height (m)	Mean annual precipitation (mm)	Mean annual temperature (°C)
Alpine meadow	90–100	0.03–0.09	411.7	-1.10 ± 1.53
Coniferous forest	60–80	16–30	589.1	1.46 ± 0.38
Mountain steppe	70–90	0.15–0.4	506.5	1.11 ± 1.03
Desert	10–30	0.3–0.6	95.4	8.99 ± 0.32
Cultivated crop	80–90	1.8–2.0	129.0	6.35 ± 0.29
Riparian forest	30–50	10–20	40.2	9.76 ± 0.49

Alpine meadows are located on the alpine and subalpine slopes at altitudes of 3000–4200 m, mainly dominated by *Kobresia* sp. The plant communities often have a large coverage, simple structure, and low grass layer. The soil is mainly alpine meadow soil, which is thin and rich in organic matter. Coniferous forests are located in the mountainous shady and semi-shady slopes at an altitude of 2400–3400 m a.s.l., and often accompanied with the steppe on the sunny and semi sunny slope, forming a compound distribution of mountain forest steppe ecotone. *Picea crassifolia* is the constructive species in the coniferous forests. The soil is mainly mountain gray cinnamon soil, with thin layer, coarse texture, and medium content of organic matter. Deserts are distributed in arid areas, with annual precipitation less than 200 mm but intense evaporation. Desert is dominated by xeric small trees, subshrubs, shrubs, or succulent plants. The soil in this area is thin, coarse, and lack of organic matter. Cultivated crop lands in the arid desert areas need sufficient water for irrigation, so they are mainly distributed in the middle reaches. Corns and vegetables are the main crops. The

riparian forests are growing under the arid desert climate. The constructive species of the riparian forests, *Populus euphratica*, can adapt to the habitat, whose atmosphere is dry while the soil is humid. The shrub layer is dominated by *Tamarix ramosissima*. Saline soil is the main soil type in this ecosystem.

2.2 Rainfall and soil moisture content data collection

Data of 12 sites (Table 2) produced by the Heihe Watershed allied telemetry experimental research (HiWATER) experiment was downloaded from <http://www.heihedata.org/>, including water content of different soil layers, and climate factors such as air temperature and rainfall (Liu *et al.*, 2011; Li *et al.*, 2013; Liu *et al.*, 2018). Measurements of soil moisture in each experimental station used CS616 water content reflectometers produced by Campbell Company of the United States (Campbell Scientific, 2006). Soil moisture sensors were installed at 4, 10, 20, 40, 80, 120 and 160 cm in most sites. The moisture contents were logged continuously with a 10-min interval during the observation period. Precipitation was measured by the TE525 sensor produced by Campbell Company, which also recorded data every 10 minutes. Rainfall partitioning data measured by traditional method was also downloaded to verify the calculating results.

Table 2 Selected eco-hydrological observation sites of the Heihe River Basin

No.	Site	Ecosystems	Dominant species	Altitude (m a.s.l.)	Observation period
1	Dadongshushan	Alpine meadow	<i>Kobresia pygmaea</i>	4101	2008
2	Jingyangling	Alpine meadow	<i>Kobresia pygmaea</i>	3750	2014–2016
3	Guantan	Coniferous forest	<i>Picea crassifolia</i>	2835	2008–2011
4	Maliantan	Mountain steppe	<i>Iris lacteal</i> var. <i>chinensis</i> + <i>Stipa krylovii</i>	2817	2008–2009
5	Pailugou	Mountain steppe	<i>Stipa krylovii</i>	2731	2006–2007
6	Hulugou	Mountain steppe	<i>Stipa penicillata</i>	2980	2011
7	Huazhaizi	Desert	<i>Kalidium foliatum</i>	1731	2013–2016
8	Bajitan	Desert	<i>Reaumuria songarica</i>	1562	2015
9	Daman	Cultivated crop	<i>Zea mays</i>	1556	2013–2016
10	Sidaoqiao	Riparian forest	<i>Tamarix chinensis</i>	873	2014–2016
11	Hunhelin	Riparian forest	<i>Populus euphratica</i>	874	2014–2016
12	Huangmo	Desert	<i>Reaumuria songarica</i>	1054	2015–2016

2.3 Methods of rainfall partitioning calculation

The soil moisture data are selected for each rainfall event, based on the criterion of the minimum inter-event time (6 hours), which is a minimum time lapse without precipitation between two rainfall events (David *et al.*, 2006; Dunkerley, 2008). Rainfall partitioning calculation starts with the calculation of accumulated infiltration quantity:

$$I = \sum_{i=1} (\theta_{ei} - \theta_i) \times k \quad (1)$$

where I is the rainfall infiltration (mm), θ_{ei} is the volume water content of the soil layer i after the rain ($\text{cm}^3 \cdot \text{cm}^{-3}$), θ_i is the volume water content of the soil layer i before the rain

start ($\text{cm}^3 \cdot \text{cm}^{-3}$), k is the thickness of the soil layer i (mm) (Wang *et al.*, 2003).

The rainfall infiltration content I is the sum of the throughfall (TF) and stemflow (SF). So the interception amount, IL (mm,) was calculated as

$$\text{IL} = \text{GR} - (\text{SF} + \text{TF}) = \text{GR} - I \quad (2)$$

where GR is gross rainfall amount (mm) in the open area.

Because rainfall < 2 mm can hardly cause the fluctuation of soil moisture (Li *et al.*, 2013), the amount of interception could not be calculated by infiltration amount in this case, and this part of rainfall events was basically ignored in the calculation.

We also drew the scatter plot and regression line to show the relationship between precipitation and rain interception.

2.4 Statistical analyses

We use one way ANOVA to analyze the differences of rainfall partitioning among the ecosystems. Pearson correlation was used to analyze the correlations between interception and rainfall characteristics. We also used multiple linear regressions to determine dominant rainfall characteristic. The descriptive statistics were performed using SPSS 20.0.

3 Results

3.1 Rainfall characteristics

For most of the ecosystems, precipitation in August was the highest, while the frequency did not show a certain regularity (Figure 2). Among all the ecosystems, alpine meadow had the highest rainfall amount ranged from 71.5 mm in June and 128 mm in August, with an average frequency of 10 each month. The riparian forest had the lowest monthly rainfall amount, which was only 10.2–28.8 mm. The mean frequency of rainfall events for all ecosystems except the alpine meadow was less than 5 times per month, in comparison with 1.8 times for the riparian forest.

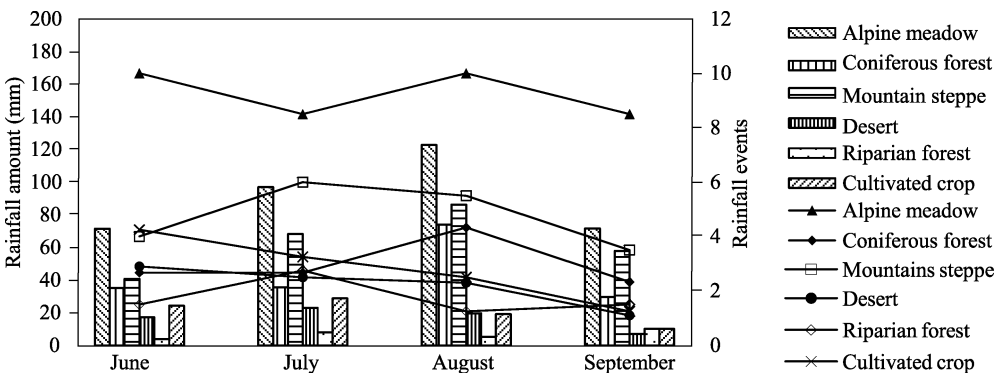


Figure 2 Monthly amount and frequency of rainfall events in growing season for typical ecosystems (Bars show the monthly rainfall amount, and lines show the rainfall events)

The most rainfall events were observed in alpine meadow (148 times), while the least was observed in riparian forest (28 times) (Table 3). The average rainfall amount was 3.9–14.7 mm for these ecosystems, and the average rainfall intensity was 0.7–1.2 mm/h (Table 3).

For all the ecosystems, 5–10 mm rainfall events occurred most frequently, with the highest contribution to the annual rainfall amount (Table 4). The 10–15 mm rainfall events also contributed largely to both the annual rainfall amount and events in most of the ecosystems. Although the heavy rainfall events (>20 mm) were less frequent, they contribute much to the rainfall amount. It should be noted that only precipitation of <10 mm was observed in the riparian forest, which had the driest climate.

Table 3 Average rainfall characteristics of typical ecosystems during observation period

Ecosystems	Observed rainfall events	Average rainfall amount (mm)	Average rainfall intensity (mm/h)
Coniferous forest	45	14.7	1.0
Alpine meadow	148	9.8	1.0
Cultivated crop	46	7.2	0.9
Mountain steppe	38	13.3	0.9
Desert	88	7.6	1.2
Riparian forest	28	3.9	0.7

Table 4 Frequency distribution of rainfall events

Rainfall event (mm)	Alpine meadow			Coniferous forest			Mountain steppe		
	Frequency		RP** (%)	Frequency		RP (%)	Frequency		RP (%)
	Times	TP* (%)		Times	TP (%)		Times	TP (%)	
0–2	8	5.52	0.83	0	0.00	0.00	1	2.63	0.38
2–5	44	30.34	10.35	3	9.68	2.13	4	10.53	3.10
5–10	44	30.34	21.27	10	32.26	14.87	15	39.47	23.61
10–15	23	15.86	19.07	7	22.58	17.21	7	18.42	17.57
15–20	12	8.28	14.30	4	12.90	14.18	4	10.53	13.84
20–30	10	6.90	16.92	2	6.45	9.50	4	10.53	19.68
30–40	2	1.38	11.22	4	12.90	27.90	2	5.26	13.90
40–50	2	1.38	6.03	1	3.23	14.20	1	2.63	7.92

Rainfall event (mm)	Desert			Riparian forest			Cultivated crop		
	Frequency		RP (%)	Frequency		RP (%)	Frequency		RP (%)
	Times	TP (%)		Times	TP (%)		Times	TP (%)	
0–2	5	5.68	1.07	9	32.14	13.96	2	4.35	1.09
2–5	28	31.82	14.01	12	42.86	41.31	14	30.43	15.95
5–10	33	37.50	34.39	7	25.00	44.74	23	50.00	50.80
10–15	14	15.91	25.18	0	0.00	0.00	3	6.52	9.65
15–20	5	5.68	12.66	0	0.00	0.00	3	6.52	15.83
20–30	2	2.27	8.07	0	0.00	0.00	1	2.17	6.67
30–40	1	1.14	4.62	0	0.00	0.00	0	0.00	0.00
40–50	0	0.00	0.00	0	0.00	0.00	0	0.00	0.00

*TP means the percentage of rainfall times. **RP means the percentage of rainfall amount.

3.2 Rainfall interception of different ecosystems

The average value of the interception amount and interception rate for each ecosystem were calculated by the difference between the rainfall amount and infiltration (Figure 3). The interception amount of coniferous forest and alpine meadows were the largest, and are significantly higher than the other four types of ecosystems (Figure 3). The alpine meadow and mountain steppe had the lowest interception rates, which were significantly lower than the others (Figure 3).

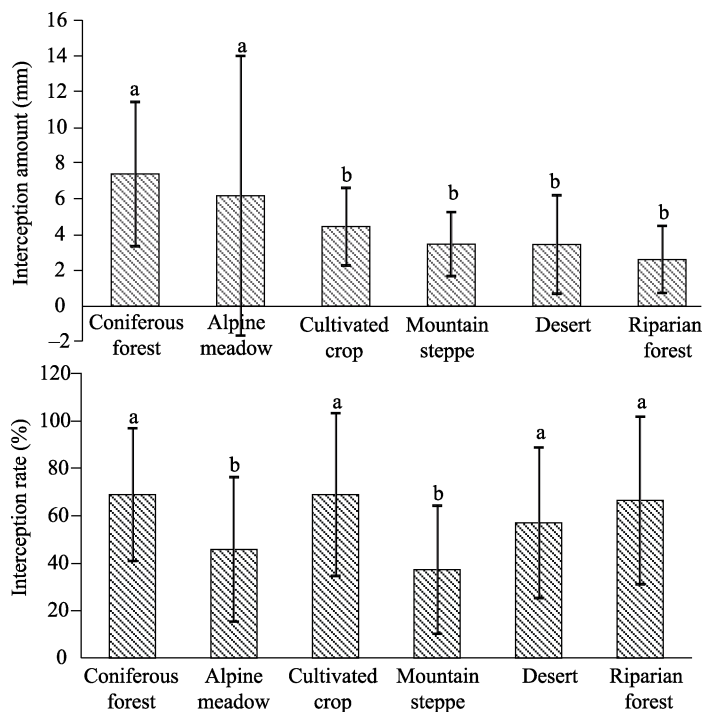


Figure 3 Average interception amount and rate of single rainfall events for each type of ecosystem

The accumulative rainfall interception with rainfall events in different ecosystems (Figure 4) showed that coniferous forest intercepted almost all the rainfall at the beginning of the rainfall event, while the desert intercepted rainfall along the rainfall event. The interception amount reached the maximum more quickly in alpine meadow and mountain steppe than other ecosystems.

3.3 Influencing factors of rainfall interception

3.3.1 Relationship between rainfall interception and rainfall amount

Significantly positive relationships were found between individual rainfall amount and interception amount for alpine meadow, coniferous forest, desert, and riparian forest, while no relationships were shown in mountain steppe and cultivated crop (Figure 5). The interception rate decreased exponentially with increasing rainfall amount in alpine meadow, mountain steppe, and desert, but it tends to be a constant in alpine meadow, when the rainfall event is more than 10 mm. The interception rate of cultivated crop, coniferous forest, and riparian forest didn't show any clear relationship with rainfall amount.

3.3.2 Relationship between rainfall interception and rainfall duration

Except for cultivated crop, all the ecosystems showed significant relationship between rainfall duration and interception amount, with a negative correlation for only mountain steppe (Figure 6). Alpine meadow and mountain steppe had significant negative exponential relationship between rainfall duration and interception rate (Figure 6).

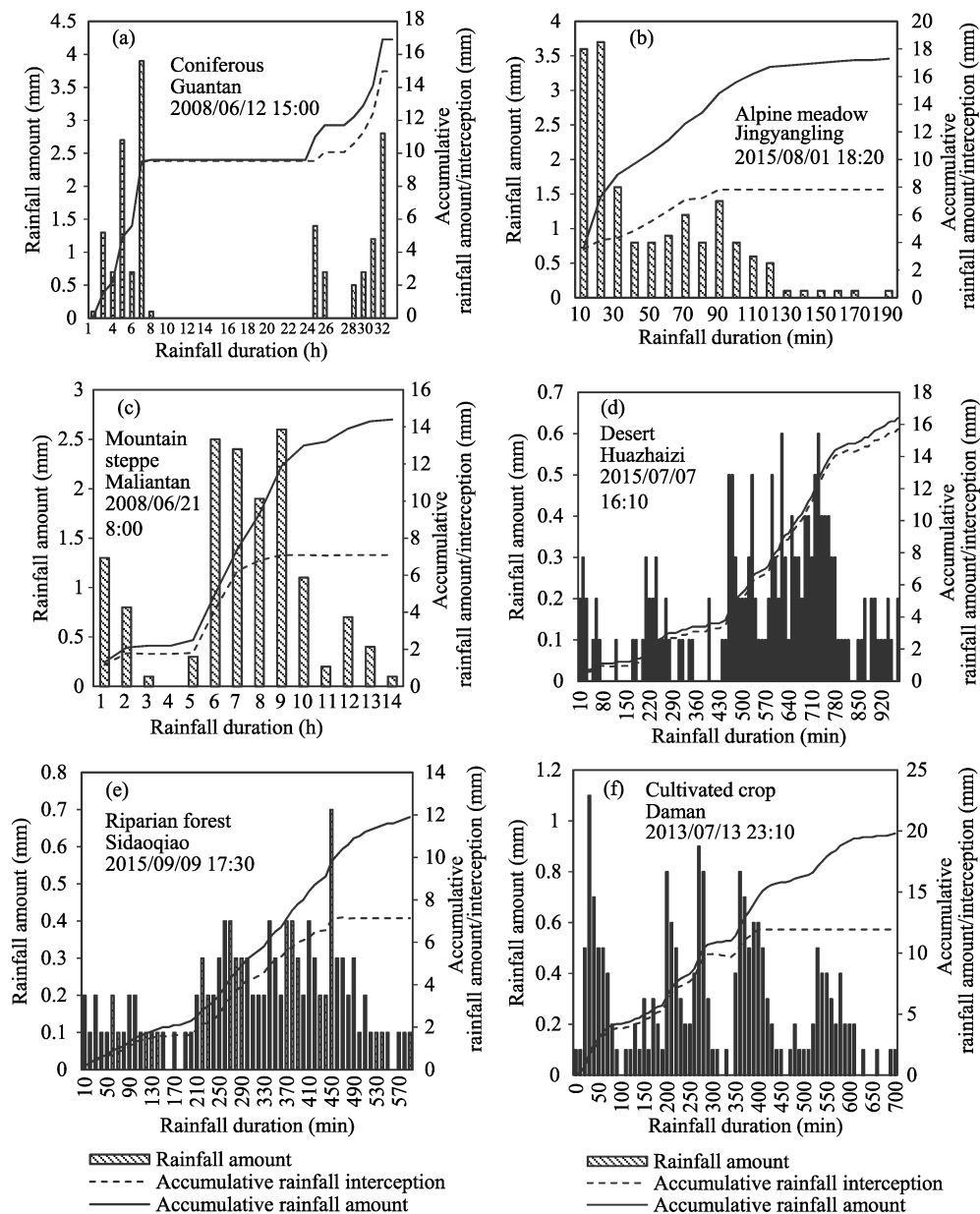
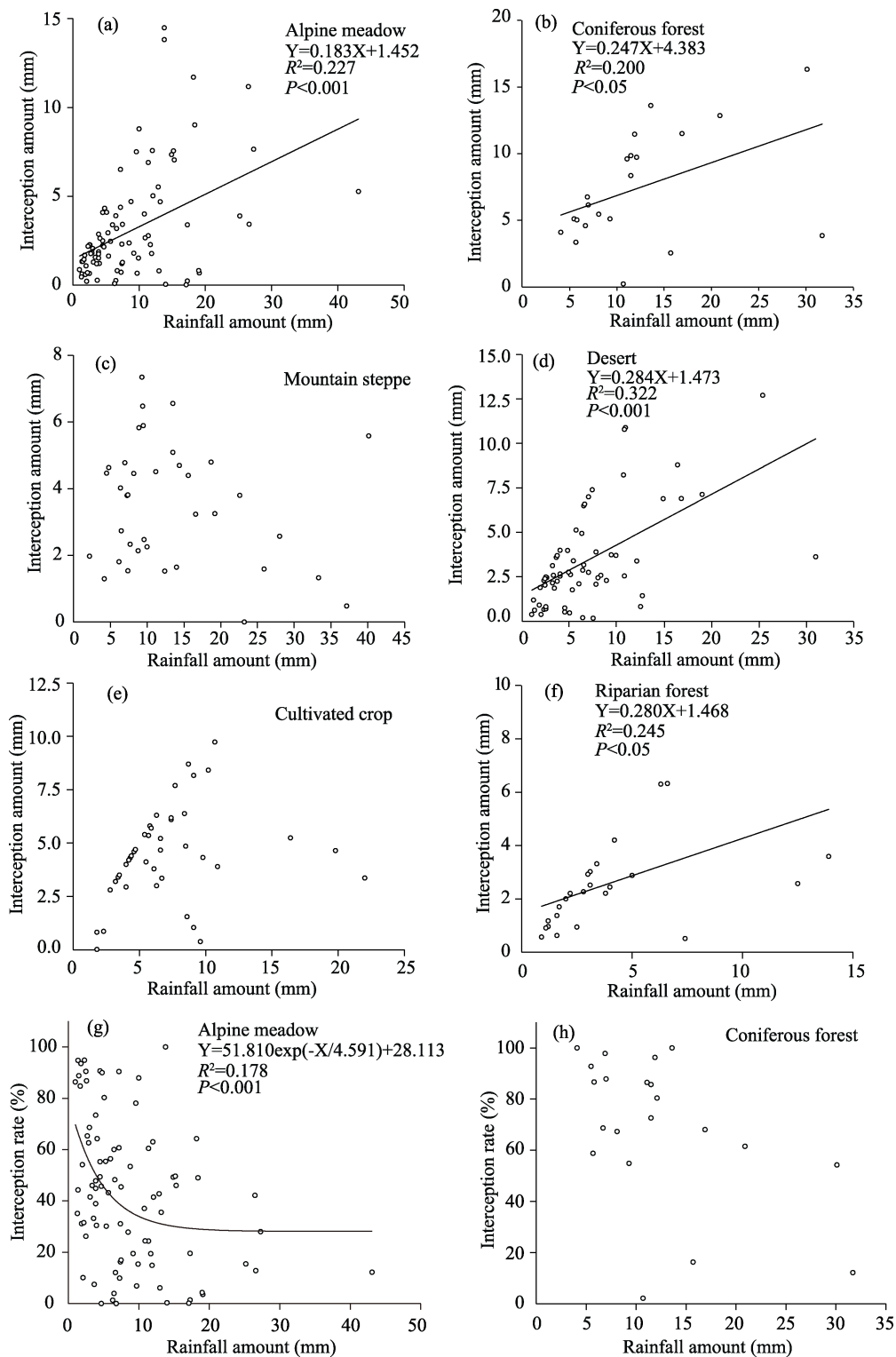


Figure 4 Rainfall interception dynamic during single rainfall event

3.3.3 Relationship between rainfall interception and rainfall intensity

Only alpine meadow and coniferous forest had significant relationship between interception amount and rainfall intensity, but they showed the opposite trends (Figure 7). The intercep-



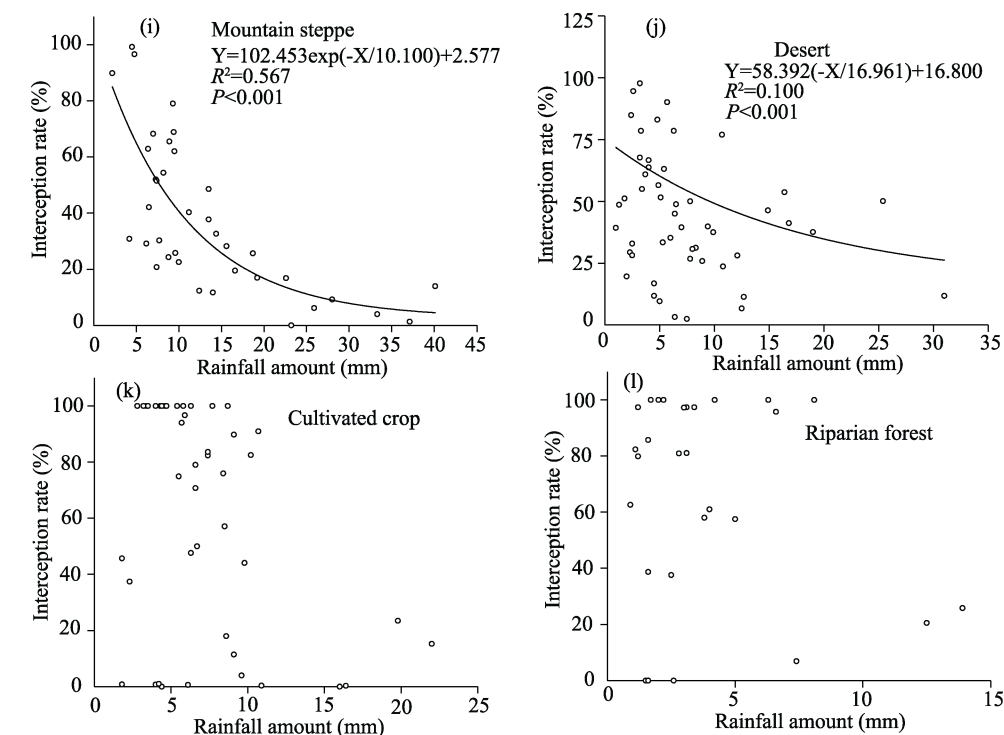
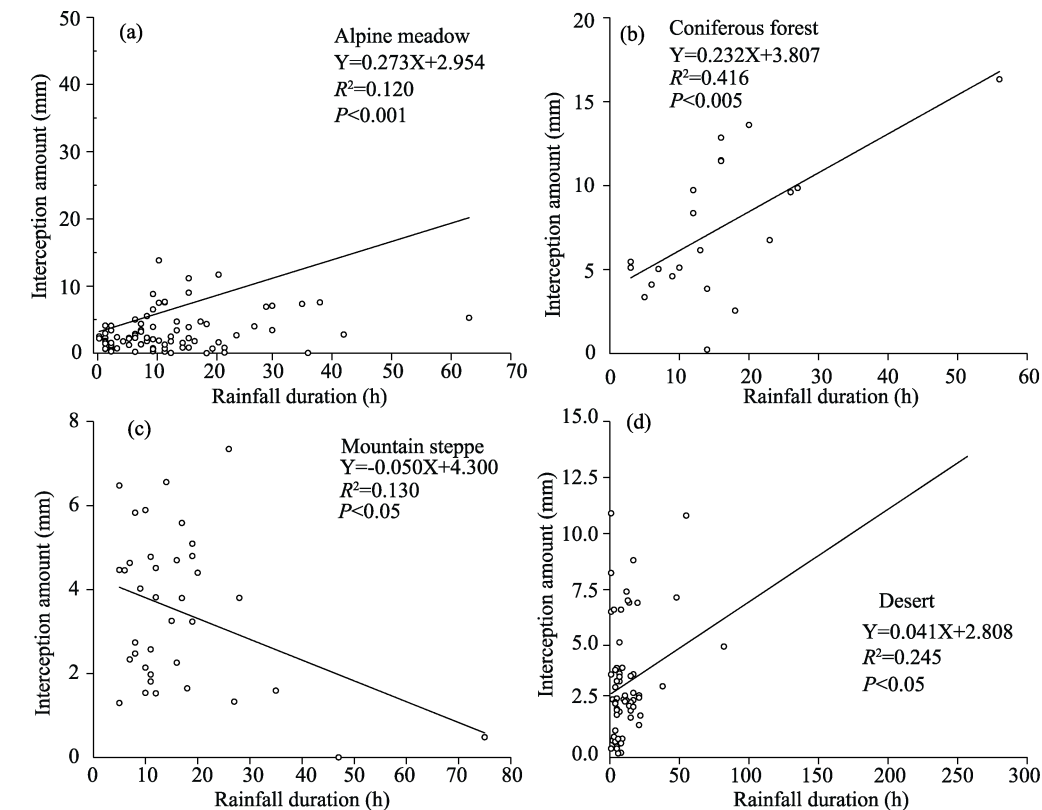


Figure 5 Rainfall partitioning as a function of individual rainfall amount (a)-(f) shows the relationship between rainfall amount and interception amount, (g)-(l) shows the relationship between rainfall amount and interception rate



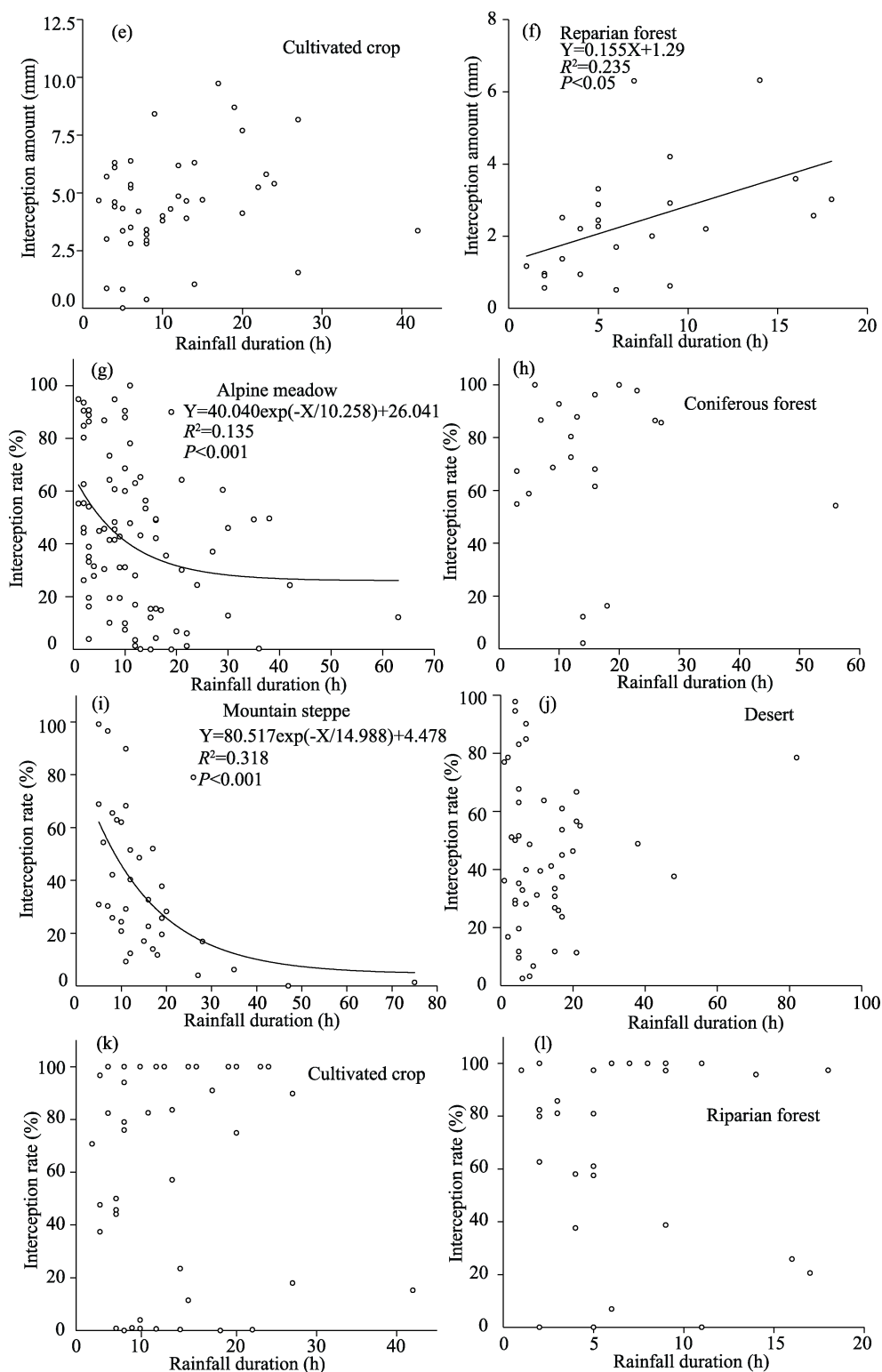
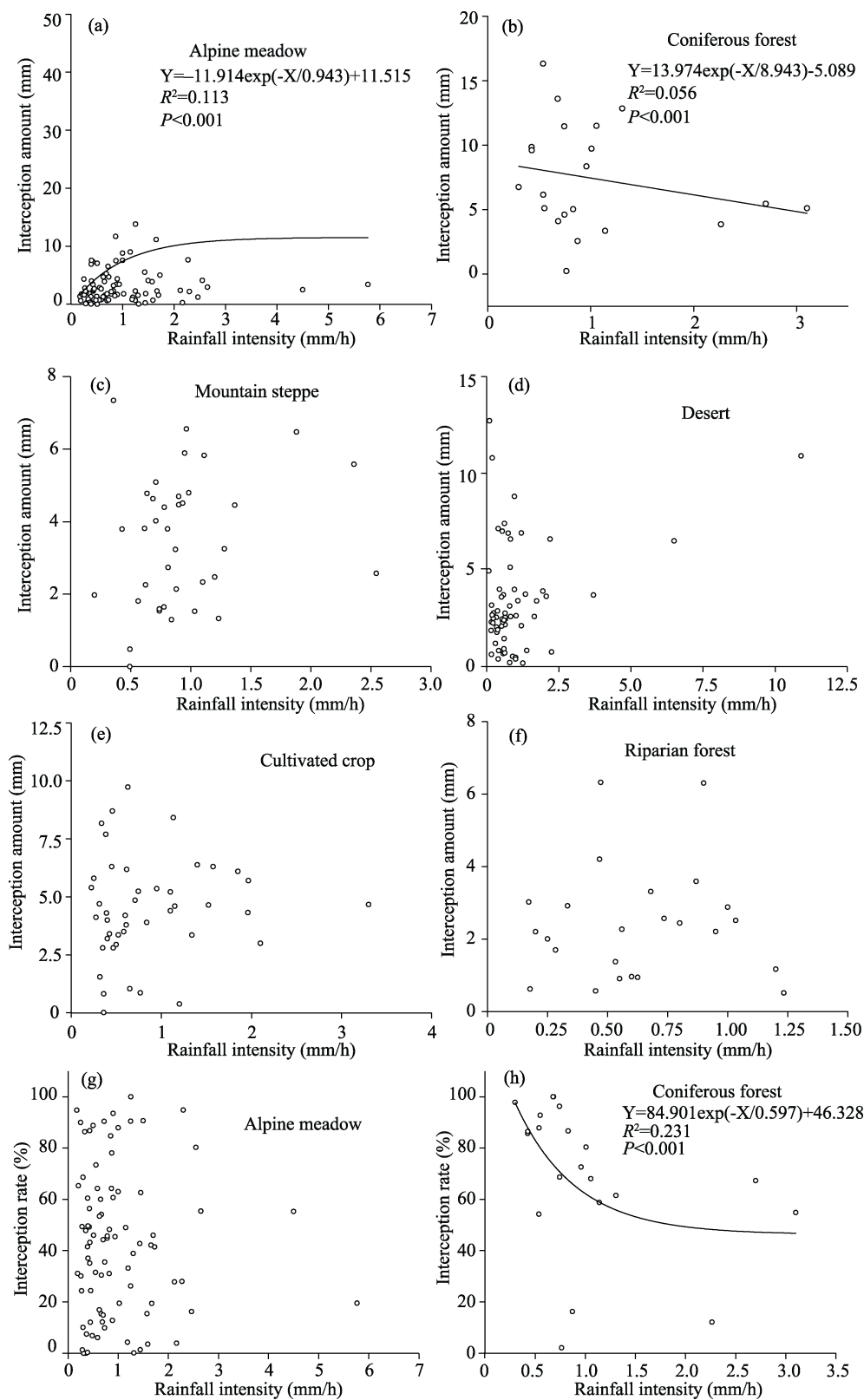


Figure 6 Rainfall partitioning as a function of individual rainfall duration (a)-(f) the relationship between rainfall duration and interception amount; (g)-(l) the relationship between rainfall duration and interception rate



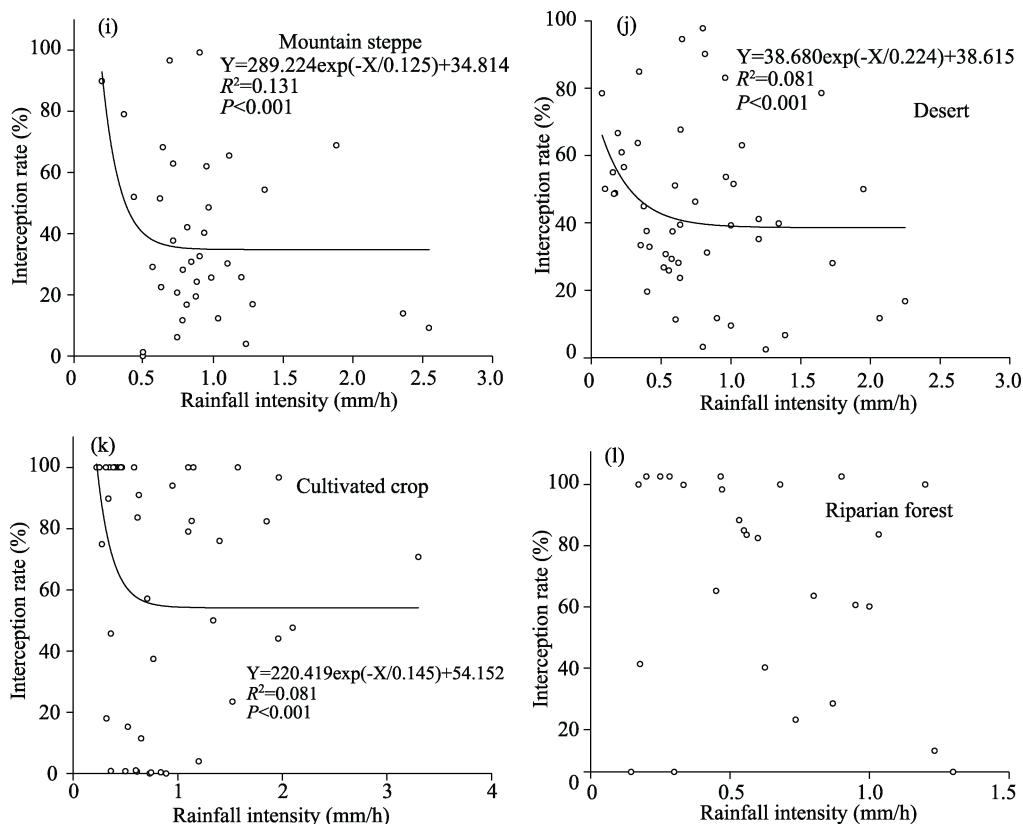


Figure 7 Rainfall partitioning as a function of individual rainfall intensity (a)–(f). the relationship between rainfall intensity and interception amount; (g)–(l) the relationship between rainfall intensity and interception rate

tion rate decreased exponentially with increasing rainfall intensity in mountain steppe, cultivated crop, coniferous forest, and desert (Figure 7). With the increase of rainfall intensity, the interception rate of the mountain steppe and desert became stable at about 40%, while that value of the cultivated crop was higher (about 60%).

4 Discussion

4.1 Differences of rainfall characteristics and interception of the typical ecosystems

Alpine meadow received most rainfall amount during the growing season (362.8 mm) among all the ecosystems, followed by mountain steppe. The rainfall amount of riparian forest, desert, and cultivated crop were all less than 100 mm, with the minimum value of 27.2 mm for riparian forest. The pattern of bulk rainfall interception amount in growing season was almost the same as that of bulk rainfall amount, with the only difference that the bulk interception of coniferous forest was higher than the mountain steppe, contrary to the rainfall amounts. Differences of average interception amount and rate of single rainfall events in these ecosystems showed in Figure 3 had different patterns with those of bulk rainfall amounts. A summary of the results of a series of rainfall interception researches in different ecosystems (Table 5) showed that the rainfall interception rate of coniferous forest

Table 5 Rainfall interception of different researches

Ecosystems	References	Study area	Main species	Vegetation coverage (%)	Annual rainfall amount (mm)	Interception amount (mm)	Interception rate (%)
Alpine meadow	Li <i>et al.</i> , 2009	Qinghai-Tibet Plateau	<i>Kobresia</i> sp.	84	269.7	0.61	12.4
	Liu <i>et al.</i> , 2013	Upper reach of Heihe River	<i>Carex atrata</i> + <i>Potentilla anserina</i>	98	Artificial	6.50	–
	This study	Heihe River Basin	<i>Kobresia pygmaea</i>	90–100	411.7	6.2	45.9
Coniferous forest	Wan <i>et al.</i> , 2016	Qilian Mountains	<i>Picea crassifolia</i>	68	367.7	2.65 ± 1.22	46.0 ± 24.9
	Hu <i>et al.</i> , 2004	Qilian Mountains	<i>Picea crassifolia</i>	–	508	4.1	–
	Tan <i>et al.</i> , 2009	Heihe River Basin	<i>Picea crassifolia</i>	79	435.5	0–5	16.7 – 75.2
	This study	Heihe River Basin	<i>Picea crassifolia</i>	60–80	589.1	7.4	69.1
	Shu, 2014	Losses Plateau	<i>Bothriochloa ischaemum</i>	70	Artificial	0–8.9	42.4
Mountains steppe	Yu <i>et al.</i> , 2012	Qinghai-Tibet Plateau	<i>Poa pratensis</i> + <i>Elymus nutans</i>	–	Artificial	0.98 ± 0.32	–
	This study	Heihe River Basin	<i>Stipa</i> sp.	70–90	506.5	3.5	57.2
	Zhang <i>et al.</i> , 2015	Tengger Desert	<i>Caragana korshinskii</i>	–	165.3	0.36 – 4.55	4.1 – 44.1
			<i>Artemisia ordosica</i>	–		0.75 – 5.29	7.15 – 46.7
			<i>Haloxylon ammodendron</i>	–		6.97 ± 2.87	10.41 ± 3.33
	Liu and Zhao, 2009	Middle reach of Heihe River	<i>Elaeagnus angustifolia</i>	–	116.8	5.37 ± 2.26	8.02 ± 2.87
			<i>Tamarix ramosissima</i>	–		5.03 ± 1.90	7.54 ± 2.36
			<i>Nitraria sphaerocarpa</i>	–		10.68 ± 3.14	15.95 ± 4.70
	This study	Heihe River Basin	<i>Kalidium foliatum</i> / <i>Reaumuria songarica</i>	10–30	95.4	4.5	57.2
	Ma <i>et al.</i> , 2015	Lab simulating test	<i>Zea mays</i>	–	Artificial	0.02 – 0.43	1
Cultivated crop	This study	Heihe River Basin	<i>Zea mays</i>	80–90	129.0	4.5	69.1
	This study	Heihe River Basin	<i>Populus euphratica</i>	30–50	40.2	2.6	66.7

and cultivated crop were the highest among all the ecosystems, which was consistent with this study. Research of Liu and Zhao (2009) in the desert in the middle reach of Heihe River showed extremely high interception amount (> 5 mm), because this result was made out under a single rainfall event with the rainfall amount as high as 67.0 mm being very rare in the desert. When ignoring this extreme high value, alpine meadow and coniferous forest, studied in the same area as ours, had the highest interception amounts, also similar as the result of this study.

4.2 Influence of vegetation characteristics on rainfall interception

One-way ANOVA analysis shows that interception amounts of coniferous forest and alpine meadow were significantly higher than those of the others (Figure 3). Among the studied ecosystems, the coniferous forest had the largest canopy height, the large canopy, and complex canopy structure, and thus a great ability to hold rain water. Hu *et al.* (2004) found that in the south of the Qilian Mountains, the *Picea crassifolia* forests, as the climax community in this area, grew well, had a great physiognomy, and thus gain the highest interception amount among all the communities. The coverage of alpine meadow in this study was as high as 90%–100%, which was the highest among all the ecosystems. Generally, the compact community structure allows the vegetation canopy to intercept more rainfall. Hu *et al.* (2004) found that the interception amount of the herbaceous layers with a coverage close to 100% was only 6.5% lower than the average of the 25 forest communities studied in the south of the Qilian Mountains. The multiple regression models of the interception, based on the vegetation coverage, rainfall intensity, and rainfall duration, also show that there is a positive, linear correlation between the interception amount and the vegetation coverage in the alpine meadow in the Qinghai-Tibet Plateau (Li *et al.*, 2009).

The interception rates of alpine meadow and mountain steppe were significantly lower than those of the other four ecosystems. The interception amount of alpine meadow increased very slowly with the increase of rainfall, so the interception rate was also low. The interception amount of mountain grassland was not significantly related to the precipitation, but the interception rate decreases rapidly with the increase of rainfall amount. Due to the much lower canopy height and leaf area index than other ecosystems, the rainfall exceeding the water storage capacity of the canopy of alpine meadow and mountain steppe was almost all infiltrated. The constructive species of alpine meadow is *Kobresia pygmaea*, while that of mountain steppe is *Stipa* sp. Li *et al.* (2009) found that the *Kobresia* and *Stipa* species always have small leaves with large leaf angle, in the process of rainfall assembling, the stem-flow is formed when the gravity exceeds the surface tension of the water drops, and is rapidly infiltrated, so the interception rate is low. In general, plant traits are one of the most influential factors for rainfall interception.

4.3 Influence of rainfall characteristics on rainfall interception

Various studies showed that, for a particular ecosystem, rainfall characteristics have a critical impact on rainfall interception (Ma *et al.*, 2012; Zhang *et al.*, 2015). The results of Pearson correlation analysis and stepwise regression analysis of the integration of all ecosystem data in this study (Tables 6 and 7) showed that rainfall amount, duration, and intensity can

Table 6 Pearson correlation analysis between interception and rainfall characteristics

Interception	Rainfall amount (mm)	Rainfall duration (h)	Rainfall intensity (mm/h)
Amount (mm)	0.604**	0.222**	0.200**
Rate (%)	−0.420**	−0.130*	0.012

* Significant correlation at 0.05 level; ** significant correlation at 0.01 level.

Table 7 Results of stepwise regression analysis

Dependent variable	Variables entered	Adjusted R^2	P value	Formula
Interception amount	P	0.362	0.000	$I=0.448P+0.991$
Interception rate	P	0.173	0.000	$IR=0.020P+0.714$

all influence the rainfall interception, especially rainfall amount.

Almost all ecosystems showed the trend that interception amount increases with the increase of rainfall, but the interception rate decreases. Interception amount and rate of cropland seem not to be associated with rainfall amount, probably because the study period was from June to September, when the corns are growing vigorously, with the traits such as height, coverage, biomass, and leaf area index changing sharply, causing a great difference in the interception process. The slope of regression line between rainfall amount and interception amount in desert and riparian forest is the largest, which may be caused by the climate in these two ecosystems. The dry climate causes strong evaporation and adds to the interception amount. The trend of the interception rate showed that most of the interception occurred in the small rainfall events, confirming the results of Price and Carlyle–Moses (2003) and Staelens *et al.* (2008). At the same time, at the beginning of the rainfall events, a large portion of the precipitation was intercepted in the canopy of plants. Along with the increase of rainfall, canopy get saturated and reaches its maximum water storage capacity, then most of the rainfall turn into throughfall and stemflow, so the interception rate decreased. In this process, the increase of interception amount was mainly caused by evaporation, an important component of interception, as indicated by Navar *et al.* (1999) and Carlyle–Moses (2004).

The correlation between rainfall duration and interception amount in mountain steppe showed an opposite trend with the others. The leaves of the plants growing in the mountain steppe are generally small. When the rainfall duration increases, the previous interception converges into water drops and falls down, reducing the amount of interception. This situation was also observed in the swamp meadow dominated by *Stipa aliena* on the Qinghai–Tibetan Plateau (Li *et al.*, 2009).

Alpine meadow is the only ecosystem with increasing rate of interception amount slows down with the increase of rainfall intensity and tends to be stable, similar to the alpine meadow on the Qinghai–Tibet Plateau (Li *et al.*, 2009), shrub in Tengger Desert (Zhang *et al.*, 2015), and alpine vegetation in Qinghai (Ma *et al.*, 2012). In contrast, Liu *et al.* (2013) found that the relationship between the interception amount and rainfall intensity fit a unimodal curve, which increases first and then reduces. Interception amount decreased with rainfall amount in coniferous forest in this study. Li *et al.* (2009) brought out that when the rainfall intensity is large, the impact force on the leaf surface is strong, which is not condu-

cive to the adsorption and storage of the rainfall, and the original partial interception on the leaf surface will also fall down. Bellot and Escarre (1998) and Owens *et al.* (2006) also found that rainfall of high intensity may yield lower interception and higher net rainfall.

4.4 Suitability of the method to calculate rainfall interception using high temporal resolution soil moisture data

As a sophisticated method which has been widely used in the calculation of evapotranspiration, analysis of hydrological process with high temporal resolution soil moisture data has been proved to be efficient (Dekker *et al.*, 2007; Soubie *et al.*, 2016; Xu *et al.*, 2017). Yu *et al.* (2012) also found that the rainfall interception estimated using the water budget method (interception equals to the difference between bulk rainfall amount and the increase of soil moisture) has a significant positive correlation with that gained by the traditional methods ($R^2=0.78$). Meanwhile, compared to the other related literatures (Table 5), it was found that the results of rainfall partitioning process calculated by high temporal resolution soil moisture data in this study were basically within a reasonable range. However, there are still some restrictions on the use of this method, such as the inability to analyze the process of interception of small rainfall that cannot cause soil moisture fluctuations. In some rainfall events, the infiltration is greater than the rainfall amount, which produces a negative interception. In spite of these, this method is very obvious for the fine depiction of the partitioning process in an individual rainfall event. Therefore, the advantages of this method can be fully brought into the analysis of the event of more than a certain amount of precipitation after calibration by the traditional method. It also needs to be further explored and optimized to realize the description of ecosystem hydrological process more accurately based on small number of experimental observations by the re-analysis of high temporal resolution soil moisture in the future (Ochsner *et al.*, 2013).

5 Conclusions

(1) Rainfall characteristics including rainfall amount, frequency, and intensity of typical ecosystems in the Heihe River Basin were different. Among the ecosystems, the alpine meadow had the highest total rainfall amount and rainfall frequency in growing season. The 5–10 mm and 10–15 mm rainfall events occurred most in all ecosystems, with the highest contribution to both rainfall amount and frequency, while larger rainfall events (>20 mm) always contributed much to the rainfall amount.

(2) Significant differences in interception amount were found among the six ecosystems. Interception amount of coniferous forest (7.4 mm) and alpine meadow (4.2 mm) are significantly higher than the others. The interception rates of the six ecosystems are coniferous forest > cultivated crop > riparian forest > desert > alpine meadow > mountain steppe. The interception rates of alpine meadow and mountain steppe are significantly lower than the others.

(3) These typical ecosystems have different rainfall partitioning process. Coniferous forest intercepted almost all the rainfall at the beginning of the rain. Desert intercepted most rainfall during all the process. Interception amount reached the maximum more quickly in alpine meadow and mountain steppe than in other ecosystems.

(4) Rainfall amount, duration and intensity all had an impact on the process of rainfall interception, among them, the impact of rainfall amount was most significant. The responses of different ecosystems to rainfall characteristics were also different.

(5) The results of rainfall interception calculated by high temporal resolution soil water data were basically within the reasonable range. Though it is still unable to analyze the partitioning process of small rainfall that cannot cause soil moisture fluctuations, analyzing rainfall interception with high temporal resolution soil moisture data can be a feasible method and needs further development in the future.

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