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RESEARCH ARTICLE

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Generation of runoff characteristics over three time periods for four typical forests in Jinyun Mountain, Chongqing City, southwest China

Abstract In order to provide a basis for water conservation in the restoration of vegetation for an urban water resource area, we studied the generation of runoff characteristics in four typical forests over three time periods in Jinyun Mountain, Chongqing City, based on the observation data of rainfall and runoff processes during the period 2002–2005. The results show that: 1) Rainfall was distributed evenly during the years 2002–2005. Annual rainfall variability was 4.46% and coefficient of variation was 0.0618. Average monthly rainfall tended towards a normal distribution $N(113.8, 4597^2)$. 2) Both precipitation and runoff can be clearly divided into a dry and a wet season. The dry season was from October to March and the wet season from April to September. Most of annual runoff of the four forest stands occurred in the wet season. The surface runoff in the wet season accounted for more than 85% of the annual runoff, and more than 75% of underground runoff. 3) Both peak values of surface runoff and underground runoff occurred in June. The relation between monthly rainfall and surface/underground runoff was fitted by the model $W = aP^2 + bP + c$. The order of annual surface runoff was as follows: *Phyllostachys pubescens* forest > shrub forest > mixed *Pinus massoniana*-broadleaf forest > evergreen broad-leaved forest. The annual underground runoff was evergreen broad-leaved forest > mixed *Pinus massoniana*-broadleaf forest >*Phyllostachys pubescens* forest > shrub forest. 4) Under similar rainstorms events, the order of the surface runoff coefficient was: evergreen broad-leaved forest < mixed *Pinus massoniana*-broadleaf forest < shrub forest < *Phyllostachys pubescens* forest. The underground runoff coefficient was: evergreen broad-leaved forest > mixed *Pinus massoniana*-broadleaf forest > *Phyllostachys pubescens* forest > shrub forest. The relation between rainstorms and surface runoff was fitted by the linear relationship: $Q = mp - n$. Both mixed *Pinus massoniana*-broadleaf forest and evergreen broad-leaved forest have better flood regulation effects on an annual and monthly basis and per individual rainstorm. The function of *Phyllostachys pubescens* forest is the worst on all three bases.

Keywords Jinyun Mountain, time periods, runoff characteristics

1 Introduction

Runoff, as an important hydrological event, is affected by watershed vegetation, soil, climate and other hydrological factors. It has become a basic indicator to evaluate the function of forests in water and soil conservation and in the reduction of flood peaks (Fang et al., 2001). The process of precipitation-runoff plays an important role in forest ecosystems and is a reflection of forest functions in soil and water conservation (Zhou et al., 2000). In recent years, studies on the runoff generation characteristics over different periods have become an urgent matter and an important issue in the area of hydrology. Hydrological phenomena change over space and time. Over long periods of time, hydrological events show considerable differences and changes in property characteristics (Li et al., 2005). At present, spatial studies on the generation of runoff characteristics are generally conducted on a small scale, such as a slope, or somewhat larger for a watershed (Phliip 1991; He et al., 1997; Swanson 1998; Li et al., 2006; Qin et al., 2006). The study on the generation of runoff characteristics over different time periods has mainly been

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carried out for changes in the river runoff (Zhao et al., 2002; Liu et al., 2003; You et al., 2005). Few studies are reported on surface and underground generation of runoff characteristics of forests.

Jinyun Mountain is located at the tail-end of the Three Gorges reservoir. It is covered by a complete, subtropical evergreen broad-leaved forest community. Already for a long time, it has been a natural laboratory for the study of water and forest conservation and management. We analyzed the changes in the generation of runoff characteristics of different stands on an annual or monthly basis and on individual rainstorm events and discuss the various hydrological effects of different stands. We hope to provide technical parameters and a scientific basis for afforestation, for the purpose of water conservation in urban water source areas.

2 Site description

The Jinyun Mountain Nature Reserve Region is located on the west bank of Wentangxia of the small Three Gorges of the Jialing River (29°45′N, 106°22′E). The highest elevation is 951.5 m with a 600 m height difference from its lowest point. Soils are mostly yellow and paddy soils (pH 4.0–4.5). The horizontal zone belongs to a typical mid-subtropical climate, with an average annual temperature of 13.6°C, an average annual precipitation of 1611.8 mm and an annual evaporation of 777.1 mm. There are rich plant species, including six major vegetation types of evergreen broad-leaved forests, warm conifer forests, *Phyllostachys pubescens* forests, evergreen broad-leaved shrub forests, subtropical shrubs, grasses and aquatic vegetation. The major dominant species are *Gordonia acuminate*, *Neolitsea aurata*, *Pinus massoniana*, *Cunninghamia lanceolata*, *Cinnamomum camphora*, *Pinus armandi* and *Symplocos setchuanensis*. The hydrological effects of four typical forests (broad-leaved forests, mixed forests, bamboo forests and shrub forest) were studied (Tables 1 and 2).

3 Methods

3.1 Rainfall observation

Climate data such as precipitation, wind speed, evaporation, air temperature, humidity, soil temperature and moisture were measured by a set of fully automated weather devices outside the forests, down to a resolution of 10 min. Precipitation data were recorded by a B-432-Z automatic hyetometer.

3.2 Runoff observation

A runoff plot (20 m × 5 m) was established in each typical stand. In all of the runoff plots, precast concrete wall panels were placed deep into the bedrock to prevent runoff

Table 1 Standard basic information of typical stands

stands	elevation /m	slope/°	slope aspect	canopy density/%	undergrowth plant cover/%	grass cover/%	soil layer thickness/cm	soil texture	litter thickness/cm
mixed *Pinus massoniana*-broad-leaved forests	760	25	NW	0.8	40	30	99	sandy loam	3.5
evergreen broad-leaved forests	825	30	NW	0.8	40	20	121	sandy loam	3.4
Phyllostachys pubescens forests	800	10	NW	0.7	10	50	90	sandy loam	1.5
shrub forests	860	8	NW	0.85	60	50	120	sandy loam	4.5

Table 2 Species composition of typical stands

stands	tree species	undergrowth plant species	herbaceous species
mixed *Pinus massoniana*-broadleaf forests	*Gordonia acuminate*, *Pinus massoniana*, *Symplocos setchuensis*, *Adinandra bockiana*	*Eurya japonica*, *Adinandra bockiana*, *Symplocos setchuensis*, *Neolitsea aurata*, *Diospyros morrisiana*	Pteridiaceae, *Woodwardia japonica*, *Diplopterygium glauca*, *Lophatherum gracile*
evergreen broad-leaved forests	*Gordonia acuminate*, *Neolitsea aurata*, *Adinandra bockiana*	*Castanopsis carlesii*, *Rhamnus esquirolii*, *Symplocos setchuensis*, *Eurya japonica*	Pteridiaceae, *Woodwardia japonica*, *Lophatherum gracile*
Phyllostachys pubescens forests	*Phyllostachys pubescens*	*Mells indica*, *Smilax china*, *Ficus viren*, *Sarcandra glabra*	Pteridiaceae, *Oplismenus compositus*, *Pilea pumil*, *Commelina communis*
shrub forests	*Symplocos caudate*, *Lindera kwangtunensis*, *Alniphyllum fortunei*, *Neolitsea aurata*	*Machilus nanmu*, *Cunninghamia lanceolat*, *Eurya japonica*	Pteridiaceae, *Hemercocallis fulva*, *Crassocephalumraben*, *Conyza canadensis*

entering from outside the runoff plots. Filter layers were established in grooves at the top of walls and connected to holes with pipes, in order to direct underground runoff to an observation room with runoff testing equipment. Drainage channels were established at the bottom of the observation room. Along at the top and two sides of the runoff plots, cut-off drains were built to intercept unobserved runoff around the slopes of the runoff plots. In the runoff plots, the slope runoff of rainfall collected in the groove sets and water-flows went into the observation room through the catheters of the groove. Every observation room was equipped with a T9801 microcomputer-based multi-channel automatic dump flow meter which monitored and recorded automatically the processes of surface runoff and underground runoff of the different runoff plots. Runoff from each plot was recorded at a resolution of 10 min.

4 Results and analysis

4.1 Rainfall characteristics

Rainfall data from 2002 to 2005 in Jinyun Mountain were used to calculate average monthly and annual rainfall. During this period, rainfall mainly occurred from May to September, i.e., 66.08% of total rainfall (Table 3). Annual rainfall characteristics were denoted by the annual rainfall variability (K) and coefficient of variation (CV) (Zhang et al., 1991). These reflect, respectively, the stability of relative changes and the rate of changes in rainfall. The larger the two indices were, the greater the changes in annual rainfall and the higher the probability of the occurrence of droughts and floods.

$$K = \sum_{i=1}^{n} \left| \frac{H_i - \overline{H}}{\overline{H}} \right| \times 100\% \Big/ n \tag{1}$$

$$\mathrm{CV} = \sqrt{\sum_{i=1}^{n} \left(\frac{H_i}{\overline{H}} - 1 \right)^2 \Big/ (n-1)} \tag{2}$$

where H_i is the rainfall and $\overline{H}$ the average annual rainfall. According to equations 1 and 2, the annual rainfall variability was 4.46% and the coefficient of variation 4.46%. Both of them were far less than 100%. The distribution of the annual rainfall is relatively homogeneous and the variation among inter-annual rainfalls is small. According to the division by Lu et al. (2006) between wet and dry seasons, there is a clear division between the two in our study area. The dry season is from October to March and the wet season from April to September. The proportion of annual rainfall in the wet season is 74.29% and only 25.71% in the dry season. The distribution of the average monthly rainfall conforms somewhat to a normal distribution N (113.8, 4597^2) (Fig. 1).

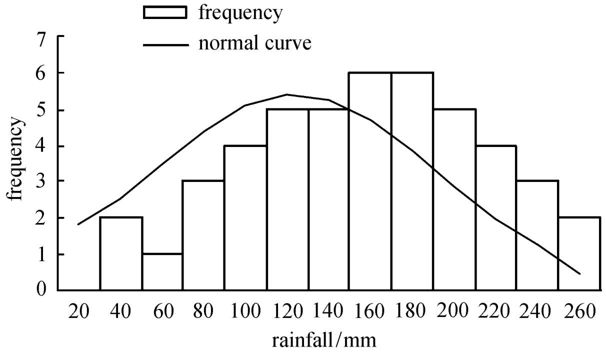

Fig. 1 Graph of normal distribution and average monthly rainfall

4.2 Seasonal distribution of runoff

Surface runoff and underground runoff occur with the same frequency as the rainfall during the wet and dry seasons (Fig. 2). The wet season was from April to September during our research period. Amounts of runoff from each typical forest in the wet season were larger than those in the dry season. Surface runoff from each typical forest in the wet season is given in the following order: evergreen broad-leaved forest (92.6%)> mixed *Pinus massoniana*-broadleaf forest (92%)> shrub forest (91%) >*Phyllostachys pubescens* forest (89.9%). Underground runoff during the wet season is presented in the order of shrub forest (98.4%)> mixed *Pinus massoniana*-broadleaf

Table 3 Monthly distribution of rainfall in Jinyun Mountain during 2002–2005

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	sum
2002	101.6	26.8	74.9	177.8	265.1	315.2	141.5	132.3	82.1	61.6	57.3	50.8	1487.0
2003	17.4	12.0	28.3	85.8	214.9	347.0	194.2	65.2	115.1	90.4	90.6	35.9	1296.8
2004	16.5	54.4	124.7	96.7	113.5	158.4	116.7	182.9	250.4	70.2	104.1	34.6	1323.1
2005	12.9	25.6	68.1	87.9	134.8	153.0	199.2	312.5	114.8	175.0	54.5	16.1	1354.4
average monthly rainfall/mm	37.1	29.7	74.0	112.1	182.1	243.4	162.9	173.2	140.6	99.3	76.6	34.4	1365.3
proportion/%	2.72	2.18	5.42	8.21	13.34	17.83	11.93	12.69	10.30	7.27	5.61	2.52	100

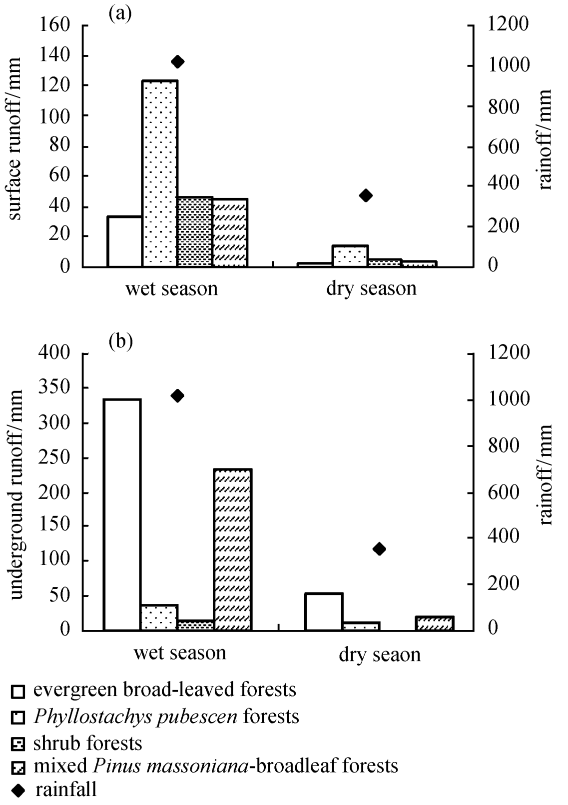

Fig. 2 Rainfall and runoff in dry and wet seasons. a: surface runoff; b: underground runoff.

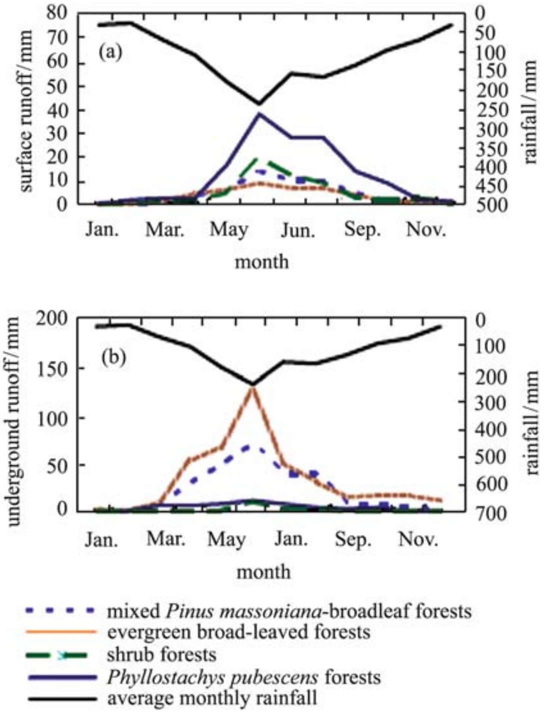

Fig. 3 Changes in runoff from different forest types. a: surface runoff; b: underground runoff.

forest (92.0%)> evergreen broad-leaved forest (86.4%) >*Phyllostachys pubescens* forest (77%).

4.3 Monthly distribution of runoff

Based on the distribution of monthly runoff during the period 2002–2005, the change of monthly surface runoff and underground water runoff of the four stands is shown in Fig. 3, which indicates that the peak flow occurred in June. Monthly surface runoff followed in the order of: *Phyllostachys pubescens* forest (137.0 mm) > shrub forest (51.4 mm) > mixed *Pinus massoniana*-broadleaf forest (48.8 mm) > evergreen broad-leaved forest (36.6 mm). Monthly underground runoff is shown in the following order: evergreen broad-leaved forest (385.0 mm) > mixed *Pinus massoniana*-broadleaf forest (250.5 mm) > *Phyllostachys pubescens* forest (46.1 mm) > shrub forest (15.2 mm). Therefore, given the same annual rainfall, evergreen broad-leaved forests are efficient in converting surface runoff into underground runoff. Evergreen broad-leaved forest had the best flood regulation effects. *Phyllostachys pubescens* forests were the worst in both aspects.

The generation of runoff of the four types of forests in our study area is of the type that belongs to a stored-full runoff. Surface runoff and underground runoff are mainly correlated with rainfall (Lu et al., 2006). Monthly runoff was calculated using the following model:

$$W = aP^2 + bP + c \tag{3}$$

where W is the monthly surface/underground runoff, P the monthly rainfall and a, b, c are coefficients to be estimated for each forest type. The calculated results are shown in Table 4. When the monthly rainfall breaches a certain level and if it continues to increase, both surface runoff and underground runoff of the four forest stands face substantial increases.

4.4 Runoff characteristics under rainstorm conditions

Observations show that if the rainfall, occurring in the four forest stands, was less than 10 mm, there would be no surface and underground runoff generated. Wang et al. (2005) reported that the response of runoff on rainstorms was obvious. Therefore, runoff characteristics are correlated with rainstorms. Most rainfalls in the study area lasted for less than 1440 min during an entire rainfall process or during specific periods. Fan’s model was introduced to calculate rainstorm standards (Fan et al., 2003)

$$K = P^2/t \tag{4}$$

where P is rainfall and t length of rainfall. When K is larger than 2, it is a rainstorm event.

Table 4 Relations of monthly rainfall and monthly runoff

runoff types	stands	a	b	c	correlation coefficient
surface runoff	mixed *Pinus massoniana*-broadleaf forests	0.0002	0.0209	−0.9757	0.924
	broad-leaved forests	0.0005	0.0291	−1.1288	0.952
	Phyllostachys pubescens forests	0.0005	−0.0497	1.5632	0.931
	shrub forests	0.0005	−0.0608	1.7837	0.931
underground runoff	mixed *Pinus massoniana*-broadleaf forests	0.0010	0.0494	−1.8956	0.950
	broad-leaved forests	0.0027	−0.2207	12.5000	0.913
	Phyllostachys pubescens forests	0.0001	0.0151	0.2957	0.900
	shrub forests	0.0004	−0.0609	1.9907	0.937

4.4.1 Characteristics of surface runoff

Single rainfall events during 2002 to 2005 were divided by K (Eq. 4). Twenty-five surface runoffs and underground runoffs under conditions of typical rainstorms were selected and analyzed. Table 5 shows that the average rainfall lasted 14.53 h. Therefore, most rainstorms in the study area are of a long-time nature. Compared with the length of a rainfall, the surface runoff of shrub forests lasted 55.8 min, 174.6 min for *Phyllostachys pubescens* forests, 188.4 min for evergreen broad-leaved forests and 201.6 min for mixed *Pinus massoniana*-broadleaf forest. The average initial abstraction duration of surface runoff of the four forest stands are in the following order: evergreen broad-leaved forests (88.6 min)>mixed *Pinus massoniana*-broadleaf forests (66 min)>shrub forests (60.5 min)>*Phyllostachys pubescens* forests (60.4 min). Evergreen broad-leaved forests and mixed *Pinus massoniana*-broadleaf forest provide useful services in flood regulation, while *Phyllostachys pubescens* and shrub forests play a much smaller role.

Given the same rainstorm events, the average surface depth of runoff from evergreen broad-leaved forests was 3.4 mm, 17.1 mm from *Phyllostachys pubescens* forests, 7.0 mm from mixed *Pinus massoniana*-broadleaf forests and 8.2 mm from shrub forests. The order of surface runoff coefficients was as follows: evergreen broad-leaved forests (0.06) < mixed *Pinus massoniana*-broadleaf forests (0.13) < shrub forests (0.15) < *Phyllostachys pubescens* forests (0.31). Therefore, evergreen broad-leaved forests enhance interception of rainfall and decrease surface runoff. It has the best flood regulation effects. Mixed *Pinus massoniana-broadleaf* forests and shrub forests are poor in this regard and *Phyllostachys pubescens* forests are the worst.

4.4.2 Characteristics of underground runoff

Underground runoff has a more obvious hysteresis effect than surface runoff. Average initial abstraction duration of underground runoff of evergreen broad-leaved forest was the shortest at 113.3 min. It was 124.3 min for the mixed *Pinus massoniana*-broadleaf forest, 230.7 min for the *Phyllostachys pubescens* forest and 372.2 min for the shrub forest, i.e., the longest (Table 5). Evergreen broad-leaved and mixed forests could quickly convert surface runoff into underground runoff, decrease surface runoff and weaken the cumulative effect of flood peaks.

Table 5 indicates that the underground runoff lasted longer than the time of precipitation. The underground runoff of mixed *Pinus massoniana*-broadleaf forest lasted 53.06 h. The underground runoff of evergreen broad-leaved forest lasted 57.78 h while it lasted for 8.92 h for the *Phyllostachys pubescens* forest and 5.24 h for the shrub forest. Extending the underground runoff can effectively slow down the conflux time of slope runoff and underground runoff and weaken the effect of channel floods.

Table 5 Characteristics of mean runoffs after 25 rainstorms of typical stands in study area

stands	rain			surface runoff				underground runoff			
	rainfall /mm	precipitation time/h	K	runoff depth /mm	runoff coefficient	initial abstraction duration /min	runoff duration /h	runoff depth /mm	runoff coefficient	initial abstraction duration /min	runoff duration /h
mixed *Pinus massoniana*-broadleaf forests	54.9	14.53	3.46	7.0	0.13	66	17.89	24.6	0.45	124.3	67.59
broad-leaved forests	54.9	14.53	3.46	3.4	0.06	88.6	17.67	30.9	0.56	113.3	72.31
Phyllostachys pubescens forests	54.9	14.53	3.46	17.1	0.31	60.4	17.44	3.5	0.06	230.7	23.45
shrub forests	54.9	14.53	3.46	8.2	0.15	60.5	15.46	1.4	0.03	372.2	19.77

Therefore, evergreen broad-leaved forests and mixed forests have the better flood regulation function.

The order of the depth of underground runoff was: evergreen broad-leaved forests (30.9 mm)> mixed *Pinus massoniana*-broadleaf forests (24.6 mm)>*Phyllostachys pubescens* forests (3.5 mm)> shrub forests (1.4 mm). The underground runoff coefficient was ranked in the following order: evergreen broad-leaved forest (0.56)> mixed *Pinus massoniana*-broadleaf forest (0.45)>*Phyllostachys pubescens* forest (0.06)> shrub forest (0.03). Evergreen broad-leaved forests and mixed forests can effectively intercept precipitation and convert it into underground runoff. They have a good hydrological function, while *Phyllostachys pubescens* forests and shrub forests are not very effective.

A good linear relationship could be established between rainfall and surface/underground runoff of a rainstorm event (Table 6). The model is as follows:

$$Q = mp - n \tag{5}$$

where Q is surface runoff (or underground runoff), p is rainfall of a single rainstorm event and m and n are coefficients.

Under the condition of a single rainstorm event, both the surface and underground runoffs were positively related with an increase in rainfall. The correlation of underground runoff to rainfall was poorer than that of surface runoff. This was mainly due to the effect of rainfall intensity. Because of a thinner litter layer in *Phyllostachys pubescens* forests and shrub forests and lower soil infiltration capacity of short-lived rainstorms, most of the rainfall came too late to be converted into underground runoff. Therefore, underground runoff of both *Phyllostachys pubescens* and shrub forests were mostly affected by rainfall, especially rainfall intensity.

5 Conclusions

Rainfalls were distributed evenly during the years 2002 to 2005. Annual rainfall variability was 4.46% and the coefficient of variation 0.0618. Average monthly rainfall came close to a normal distribution N (113.8, 4597^2).

Both precipitation and runoff can be clearly divided into a dry and a wet season. The dry season is from October to March and wet season from April to September. Most of the annual runoff of our four forest stands occurred during the wet season. The surface runoff in the wet season accounted for more than 85% of the annual runoff and for more than 75% of underground runoff.

Both peak amounts of surface runoff and underground runoff occurred in June. The relation between monthly rainfall and surface/underground runoff was fitted by the model

$$W = aP^2 + bP + c. \tag{6}$$

The order of annual surface runoff was as follows: *Phyllostachys pubescens* forest (137.0 mm)>shrub forest (51.4 mm)>mixed *Pinus massoniana*-broadleaf forest (48.8 mm)>evergreen broad-leaved forest (36.6 mm). The order of annual underground runoff was evergreen broad-leaved forest (385.0 mm)>mixed *Pinus massoniana*-broadleaf forest (250.5 mm)>*Phyllostachys pubescens* forest (46.1 mm)>shrub forest (15.2 mm). Evergreen broad-leaved forests have the best flood regulation effects. *Phyllostachys pubescens* forests are the worst.

Under the same rainstorm conditions, the order in terms of the surface runoff coefficient was evergreen broad-leaved forest (0.06) < mixed *Pinus massoniana*-broadleaf forest (0.13) < shrub forest (0.15) < *Phyllostachys pubescens* forest (0.31) and the order of underground runoff coefficient was evergreen broad-leaved forest (0.56)> mixed *Pinus* massoniana-broadleaf forest (0.45)>*Phyllostachys pubescens* forest (0.06)>shrub forest (0.03). The relation between rainstorms and surface runoff was fitted quite well by a linear relationship $Q = mp - n$.

Both mixed *Pinus massoniana*-broadleaf forests and evergreen broad-leaved forests have excellent monthly and annual flood regulation effects. In the medium and long-term, these forests perform their role in water conservation and flood regulation very well. During rainstorms, they can lessen flood peaks to reduce flood hazards. Over longer periods of time, the function of shrub forests is not very constructive and those of *Phyllostachys pubescens* forest are the worst.

Table 6 Relations between rainstorm and runoff

runoff types	stands	m	n	correlation coefficient	number of sample
surface runoff	mixed *Pinus massoniana*-broadleaf forests	0.1878	3.7743	0.905	25
	evergreen broad-leaved forests	0.1591	5.3262	0.801	25
	Phyllostachys pubescens forests	0.5465	14.4350	0.888	25
	shrub forests	0.2515	6.5321	0.885	25
underground runoff	mixed *Pinus massoniana*-broadleaf forests	0.7821	14.1340	0.832	25
	evergreen broad-leaved forests	0.8553	11.4010	0.869	25
	Phyllostachys pubescens forests	0.0736	0.0995	0.760	25
	shrub forests	0.0519	1.1819	0.730	25

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