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Scale effect on runoff in alpine mountain catchments on China's Gongga Mountain

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Abstract

Finding an effective method to upscale or downscale hydrological processes is the central concern in hydrological research. The aim of this paper is to investigate a powerful, regulated relationship between runoff and catchment area, and establish the runoff scale transfer model for Gongga Mountain in China. We chose a series of catchments in which the contributing areas ranged from 0.41 km^2 to 80.5 km^2 to monitor the hydrological processes and meteorological conditions since 1990. To identify the nature and causes of variation in the runoff response to the size of catchments, a two-stage scaling method was proposed to describe the processes of runoff scaling. The results indicated that runoff had a different statistical relationship in different seasons and the related parameters were also different. The scaling models indicated a higher simulation efficiency and precision between the observed runoff and the calculated runoff, and they also provided a practical way for upscaling or downscaling in an alpine mountain watershed. For alpine mountain catchments, the results showed that the vegetation type and cover might be important factors for the runoff response to the scale effective.

1 Introduction

The scale issue in hydrological processes refers to an understanding of the potential upscaling or downscaling methodologies, and developing models for scaling the dominant processes at different scales and for different environments. Upscaling or downscaling usually refer to hydrologic properties at a support that is larger or smaller than the one for which data are available (Martín et al., 2005). The process of transferring parameters from neighboring catchments to the catchment of interest is generally referred to as regionalisation (Blöschl and Sivapalan, 1995). The choice of catchments from which information will to be transferred is usually based on some sort of similarity measure. One common similarity measure is spatial proximity, based on the rationale that catchments that are close to each other will have a similar regime because climate and catchment conditions will only vary smoothly in space (Merz and Blöschl, 2004).

Predicting runoff response in ungauged catchments is emerging as one of the major issues in hydrological science (Sivapalan, 2003). Recent catchment hydrological studies on the scaling issue indicate that the scale effects vary significantly between different contexts and experimental methodologies. When monitoring surveys involved catchments larger than 1 km^2, the scale effects could be even more divergent (Cerdan et al., 2004). Comparing scale effects from plots to catchments, Cammeraat (2002) showed that the relative expression of different processes could be subject to thresholds and change with scale, from the dominant role of biological processes to abiotic processes with increasing scale, but that the evolution of the system was highly dependent on the interactions and feedback-dominated processes at finer scales. One of the factors that make scaling so difficult is the heterogeneity of catchments and the variability of hydrological processes. Different forms and degrees of heterogeneity need to be taken into account in hydrological modeling (Becker and Braun, 1999). Blöschl (2001) suggested that when upscaling, we should develop models to focus on the dominant processes that control the hydrological response in different environments and at different scales. Therefore, it is necessary to study the scale issue in different catchments with different geographic and climate or vegetation conditions.

Rainfall and runoff relationships are widely used as a diagnostic variable of runoff process studies and an important input parameter in hydrologic design (Merz et al., 2006). However, simulations are particularly difficult to make in alpine regions, where data are sparse and the spatial variability of both precipitation and physical controls on runoff generation is huge. Most regional scale studies, so far, have analysed a relatively limited number of events (Merz et al., 2006). We have very limited knowledge of the evolution of the hydrological response with scale in this context. There are few studies focused on the scale issue in alpine watersheds, and it is unclear how scale affects the rainfall-runoff relationship in those regions.

Mountains play an important role as water reservoirs for lowlands. In particular, they supply water for human activities during dry seasons, either directly through surface runoff or indirectly through infiltration and aquifer recharge (Bayard et al., 2005). Alpine hydrological research has predominantly been focused on snow, glacier, and permafrost hydrology (Tenthorey, 1992; Singh, 2001). There is a lack of studies, as well as tools, related to different scale effects on runoff in alpine hydrology. This lack of research in alpine areas was our motivation to initiate this study with the principle aim of estimating the impact of scale effects on alpine regions.

Gongga Mountain is an important alpine region in southwest China; it has an intact vertical zone from the Subtropical Zone to the Frigid Zone, with abundant biodiversity. To clearly delineate the influence of scale effect of runoff processes on region, we selected and investigated a typical alpine watershed in Gongga Mountain. Based on the hydrological processes monitored in the research watershed from 1990 to 2008, the objectives of the present study were (1) to ascertain and quantify the scale effect for seasonal hydrological processes, and (2) to establish quantified simulated models containing parameters that link processes to the scale in seasonal runoff processes in the alpine watershed.

2 Materials and method

2.1 Site description

The study area is located in the middle and south sections of the Daxue Mountain Range, and on the southeastern fringe of the Qinghai-Tibet Plateau (101°30′–102°15′ E and 29°20′–30°20′ N). The altitude of the highest peak in the mountain range is 7556 m a.s.l, which is the summit of Hengduan Mountain. The climate on Gongga Mountain belongs to the transition band between China's eastern monsoon subtropics and the Frigid Area of the Tibetan Plateau (Fig. 1). The eastern slope of Gongga Mountain is a windward slope with wet monsoon climate; the annual mean air temperature is

3.8 °C. The average annual precipitation is 1940 mm, 60.6% of which occurs from June to September. Other detailed features and information about this site are available in the literature (Titov, 2007; Cheng and Luo, 2004; Luo et al., 2005; He and Tang, 2008).

The research site was characterized by a subtropical mountain humid monsoon climate. It had an intact vertical zone from the Subtropical Zone to the Frigid Zone, with abundant biodiversity. The characteristics of the research catchments are shown in Table 1. Gauging instruments were installed at the outlets of the four catchments. The spatial scales of the four catchments ranged from 0.41 km^2 to 80.5 km^2. Some characteristics of the catchments are presented in Table 1.

2.2 Measurements

The observation system at the Gongga Alpine Ecosystem Observation and Experiment Station was established in 1988. The alpine hydrological observation system is one of the most important sections. This observation system contains four catchments, one groundwater observation site, one forest runoff field, and one meteorological station. The meteorological station was established in the watershed to measure climatic factors.

The runoff observation site contains glacier hydrological observations and forest hydrological observations. Catchment 1# is a glacier, and the others are located in forested areas (Fig. 1). At runoff observation points, surface runoff velocities and water levels were measured with automatic water level gauges placed at the outlets of the sites. The air temperature and precipitation observation locations were located near the outlet section.

2.3 Data analysis

Self-similar processes have been successfully used in modeling data arising in a variety of different scientific fields, including hydrology and geophysics (Martín et al., 2005). Hydrological processes are considered to be self-similar, and the interrelations of statistical variables at different scales can be determined by a relatively simple scaling rule (Van de Giesen et al., 2000; Chang and Ding, 2001). Fractals have similar properties that are used in analyses of the structure of stream networks. Fractal models contain parameters that relate features at one scale to those at all other scales, and as such, they present an appealing methodology for linking processes across scales. Applications of fractal geometry in soil and hydrological studies have grown exponentially (Pachepsky et al., 2000), and the power spectrum fractals that follow are the most commonly used in hydrology. For a hydrologic variable X, at the scale α, there must be a function describing the variable: $F = X(\alpha)$. If the scale changes to $k\alpha$, then for a self-similar hydrological process, the following relationship holds (Voss, 1988; Chang and Ding, 2001):

$$\{X(k\alpha)\} = k^{\theta} X(\alpha) \tag{1}$$

where θ is called the scaling exponent or scaling factor. The spatial-correlation structure of scaling factors describes the variability in the field. This results in considerable simplicity and enhanced understanding, as well as convenience in modeling a heterogeneous watershed for its hydrologic responses (Pachepsky et al., 2003; Kozak and Ahuja, 2005). Chang and Ding (2001) analyzed the interactions between peak runoff rates Q and their corresponding spatial scales (drainage area F), and found the following relationship:

$$Q(kF) = k^{\theta} Q(F) \tag{2}$$

In this study, the processes of glacier and snow freezing and thawing and the annual distribution of rainfall had a significant effect on the rainfall-runoff relationship and its dynamics. For the hydrographical observation, by selecting the peak point and rising point of precipitation as the division nodes, the annual runoff processes were divided into two stages (Fig. 2): a) the dry season (from December to April), which was characterized by little precipitation and runoff; and b) the wet season (May to October), which was represented by increases in runoff in the channel and precipitation. Figure 2 shows the seasonal variations in precipitation, temperature, and the runoff percentage that accounts for annual runoff.

To derive the scaling exponent for the transformation of rainfall-runoff dynamics across different spatial scales, a two-stage parameter scaling method can be proposed. The process consists of three steps:

1. To establish the relationship between runoff and precipitation (or temperature) for different spatial scale sub-catchments:

$$Q_k = F(P_k, a_k) \tag{3}$$

where subscript k refers to sub-catchments at different spatial scales; Q_k and P_k refers to runoff and precipitation in the catchment at spatial scale k. a_k is a parameter set that may include different parameters. For a given k, using Eq. (3), data pairs $\{k, a_k\}$ of spatial scales (e.g. sub-catchment area) versus different parameters in Eq. (3) can be obtained.

2. The data sets were normalized, and each parameter in $a_k$was regressed as a function of scale k:

$$\{a_k\} = \{R(k)\} \tag{4}$$

Step (2) was completed for all the parameters a_k, and then we have finished the first stage of scaling for the rainfall-runoff relationship. Using statistical methods available in SAS 8.1 (SAS Institute 2000), we generated a regression model linking a_k and scale k from mean daily data collected in different catchments.

3. Equation (4) above is substituted into (3), and then field measured data were used to test the fit and validate the model with R^2, a relative error and efficiency coefficient (Nash-Sutcliffe coefficient). After the test, an improved runoff equation expressed in terms of scales was obtained:

$$Q_k^R = F(P_k, \{\mathrm{R}(k)\}) \tag{5}$$

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Based on Eq. (5), we obtained a scaling exponent of $k^{\theta} = Q_k / Q_k^R$, and a formula to apply to scaling of the rainfall-runoff relationship for a specific catchment.

3 Results

3.1 Scale effects for runoff

The annual runoff distributions of the four catchments were not equal (Fig. 2, Table 2). For the entire year, rainfall in the period from May to October was significantly higher than the other months, indicative of the widespread humidity at this time. The wet season is from May to October in one year, and then the dry season is from November to April of the next year. The peaks in runoff for the four catchments corresponded with the rainfall and temperature peak, except in catchment 4#, where the peak was in September, which lagged one or two months behind the rainfall peak. Correlation analysis indicated that there was a significant correlation between temperature and runoff in the dry season, and the runoff was correlated with rainfall and temperature in the wet season. This is the basis of this research.

The annual mean runoff in different catchments is described in Table 2. The runoff generally decreased as the area decreased from 80.5 km^2 to 0.41 km^2.

3.2 Scaling of the perennial monthly temperature-runoff relationship during the dry season

Perennial mean monthly temperature, rainfall, and runoff data for the dry season from 1990 to 2006 in the four catchments were collected and analyzed. The primary factor affecting runoff in the dry season was the temperature. Temperature and runoff were significantly correlated, and showed an exponential relationship for each gauging site during the dry season (Fig. 3). Based on this relationship, an exponential regression for each catchment was built for the wet season during 1990 to 2006. The statistical regression results are shown in Table 3.

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Based on the statistical regression equations for the different spatial scale catchments, the data series $\{k, a_k\}$ of spatial scales (e.g. catchments area) and the related parameters in the *R*-*T* regression equations can be built. The scaling model was derived after the catchments area data were normalized, and the correlation between the spatial scales and the related parameters were analyzed. The scaling model is as follows:

$$Q = (0.0532k - 0.0183)e^{0.1891k^{(-0.1765)}T} \tag{6}$$

where k is the spatial scale (watershed area index), and T is the temperature (°C). This model was applied to all the catchments to test its general applicability in the dry season runoff processes from 1 November 2007 to 30 April 2008, and the results are summarized in Fig. 4. The results showed a better consistency between the calculated and observed runoff values at all the gauging sites (Table 4). In general, the model gave a good simulation of the dry season. The R^2 between the simulated and observed runoff ranged from 0.56 to 0.99 with an average of 0.79 for all the catchments. The Nash coefficients, which represent the efficiency of model (Nash and Sutcliffe, 1970), ranged from 0.74 to 0.81 with an average of 0.77. The relative error ranged from 0.1 to 0.24. The results showed that the scaling model could be used to simulate the dry season monthly hydrographs across different spatial scales in the research area.

3.3 Scaling of the perennial monthly rainfall, temperature, and season relationship during the wet season

The primary factors affecting runoff in the wet season were temperature and rainfall. In an analysis of the runoff data during the wet seasons from 1990 to 2006, the perennial monthly mean runoff had a significant relationship with rainfall and temperature ($R^2 > 0.64$, $p < 0.01$). A nonlinear regression was conducted for the runoff, rainfall, and temperature data for the wet seasons from 1990 to 2006. A multiple regression model of the data pairs was established using regression equations. We obtained a nonlinear scaling relationship after normalizing the set of catchment area data and analyzing the statistical regression relationship between the two data sets. Using the method described above, a multiple regression model was established based on analyzing the scaling of the runoff in different catchments, and the scaling model is as follows:

$$Q = 0.0007e^{(0.01k)T} + (0.0004k - 0.0002)P + (0.001k^2 + 0.04k - 0.01) \quad (7)$$

where k is the spatial scale (watershed area index), T is the temperature (°C), and P is the rainfall (mm).

By using the above Eq. (7), the wet season runoff processes in 2007 and 2008 were simulated for the different spatial-scale catchments, and the results are shown in Fig. 5. The R^2 between the simulated and the observed data from the wet season runoff ranged from 0.61 to 0.80, with an average of 0.71 (Table 4). The Nash coefficients ranged from 0.65 to 0.82, with an average of 0.74. These results still suggest that Eq. (7) can be applied to the scaling of the wet seasons across different spatial-scale catchments.

Gupta (2004) found that the scaling parameters could be estimated empirically by using the slopes and intercepts of the logarithmic linear relationships between peak flows and watershed areas. Runoff shows a different statistical relationship in different seasons and the related parameters are also different.

However, the simulation efficiency for the scaling models in the wet season showed a different trend (Fig. 8). The simulated runoff peak in catchment 1# was lower than the observed value, and the other showed a different form. This might be partly caused by the physical processes governing flooding in river basins, which were highly variable in space and time (Gupta, 2004; Merz et al., 2006). The efficiency and result of the scaling models were under the influence of catchments characteristics such as geological and geomorphological conditions, vegetation cover, etc.

3.4 Scaling of daily runoff processes

Changing from a monthly scale to a shorter time scale, we expected that the effect of the catchment runoff simulation would become even more significant. Regression equations of daily runoff scale transformation were established during 2004 to 2007 with the same seasonal divided method mentioned above. The statistical regression models of daily runoff in the dry and wet seasons are:

$$\text{Dry season}: Q = (0.0014k^2 - 0.016k + 0.0606)e^{(-0.0001k^2+0.0097k+0.1)T} \quad (8)$$

Wet season:

$$Q=(0.0004k^2-0.0006k+0.0019)e^{(0.0008k^2-0.008k+0.1)T}+(0.00004k^2+0.00007k+0.0003)P \quad (9)$$

where k is the spatial scale (watershed area index), T is the temperature (°C), and P is the rainfall (mm). By using the above formulas, the dry and wet season runoff processes in 2008 were simulated for the different spatial-scale catchments. The results are shown in Table 4 and Figs. 6, 7, and 9.

The simulated results are shown in Table 4. The results of the daily mean runoff simulation showed the same trend as the results of the monthly – that the validity of catchment 3# was worse than the others. The results for daily scale were better than for the monthly. The R^2 between the simulated and the observed data for the dry season runoff ranged from 0.73 to 0.86, with an average of 0.79. The Nash coefficients ranged from 0.63 to 0.95, with an average of 0.82. Except for catchment 3#, for which the Nash coefficient was 0.63, the Nash coefficients were all greater than 0.80.

The R^2 between the simulated and the observed data for the wet season runoff ranged from 0.52 to 0.78, with an average of 0.70. The Nash coefficients ranged from 0.62 to 0.73, with an average of 0.68. The results for catchment 3# were the poorest of all the catchments like the results from the dry season. The R^2 for the other three gauging sites were all greater than 0.72 and the Nash coefficients were all greater than 0.71. The relative error had the same characteristics.

The simulation results for the daily scale had the same trend as the monthly scale (Figs. 8 and 9). The simulated runoff peak for catchment 1# was lower than the observed value, and the others show a different form.

4 Discussion and conclusions

In the subalpine area of southwest China, in each season, the dominant factors controlling surface runoff processes were different. The temperature was the main factor that controlled the runoff processes in the dry season. For the multi-scale catchments with areas from 0.41 km^2 to 80.5 km^2 in this study, different runoff process scaling models were used for different seasons in terms of daily and monthly runoff. For this reason, a two-stage scaling method was proposed to establish scaling models for the dry season runoff and wet season runoff at monthly and daily scales. For catchments, the different scaling models demonstrated different simulation precisions and model efficiencies. Comparing the monthly simulation results with the daily simulation results, the simulated daily runoff agreed with the monthly runoff. However, the precision of the daily simulation was higher than the monthly scale; the average Nash coefficient for one year was 0.86 on a monthly scale and 0.88 on a daily scale at the same time.

Underlying surface heterogeneity is one of the major factors causing spatial heterogeneity and scale effects in hydrological processes. At the scale of the catchments examined in this study, the soil moisture and land cover were the main factors controlling the rainfall-runoff processes and runoff coefficient distribution (Merz et al., 2006). Because of the underlying surface variation, runoff was different between the different catchments under consistent climate conditions. The underlying surface situation of the catchments always includes geographic position, topography and geomorphology, vegetation character, geological structure, and so on. The random combination of these factors on spatial scale constitutes the variation in the underlying surface; such differences can lead to a diversity of runoff yield conditions in the catchments.

In the research area, vegetation cover was an important factor causing the spatial-temporal variation in rainfall infiltration and watershed flow concentration, which resulted in spatial hydrological heterogeneity. The surface runoff in catchment 1# was a glacial river and the glacial melt water was the main recharge source, and accounted for 50% of all the runoff. The annual variance in runoff had a significant correlation with temperature changes. Regardless of the monthly or daily model, the precision for the dry season was higher than that for the wet season in the simulation results for catchment 1#. With the coming of the rainy season, runoff began to increase because of the increased rainfall. It is generally thought that the lower the vegetation coverage, the higher the runoff with the same amount of precipitation (Sidle et al., 1995). In catchment 1#, the forested area accounted for 19.25% of the total catchment area. It was the most poorly vegetated catchment in the entire study basin, which might be the reason its observed runoff was higher than the simulated one. Compared with catchment 1#, catchments 2#, 3#, and 4# were forested zones with abundant species and vegetation coverage of more than 73%. Abundant forest cover can decrease rainfall infiltration rate that can lead to the decrease of runoff, the simulated runoff is higher than the observed runoff in the other catchments. From these results, it can be inferred that high vegetation cover helps attenuate flood peak flow, which leads to lower runoff and an overestimation of peak flow in the simulation.

In addition, the vegetation type, soil characteristics, and geological structures are also important factors affecting the precision of the results. Catchment 3# had poor simulated precision in the forest zone catchments. Gao et al. (2002) researched the hydrological process in the research area on Gongga Mountain. He found that the litter layer had an obvious hydrological function in soil water retention, and the effective water retention of soil in the slope deposits is 3–4 times more than that of glacial till soil in the same type of forest land. Forest and shrub areas in catchment 3# is 90% account for the total area. In research area, a heavily forested zone in the lower altitude area had abundant moss and humus on the land surface, which made the hydrological function of the vegetation more distinct. At the same time, the forest soil type was a thick slope deposit that could have led to strong storage capacity. The river cuts into the bedrock, so this river accepts some groundwater recharge. The vegetation conditions, geological characteristics, and recharge sources were complex, which directly affected the precision of the simulation results. However, the model is still efficient for this catchment; the complex underlying surface conditions only affected the precision of the result.

Although catchment 4# had the highest vegetation cover and the soil type of this area was slope deposit that had better soil water retention, the simulation's precision for this area was not the worst. This catchment was the smallest region; its regulation and storage capacity was not as strong as the larger region; thus, the runoff was sensitive to changes in the rainfall. In addition, the higher altitude resulted in less groundwater recharge in this region.

Our statistical approach is widely applied to obtain the scaling of runoff processes across different spatial scales. Gupta and Waymire (1998) systematically analyzed the spatio-temporal variability of precipitation and runoff, and proposed a statistically simple scaling and multiscaling approach. However, the impact of vegetation on hydrological spatio-temporal variability was not considered in their methods. Land cover heterogeneity is one of the major factors that causes spatial heterogeneity and scale effects in hydrological processes (Merz and Blöschl, 2004; Zhang et al., 2008). Sidle et al. (1995) found that forest cover had a comparatively large impact on the interrelationships of storm flow across different spatial scales. Cerdan et al. (2004) also demonstrated that land cover and land use patterns were the main driving force behind variation in the runoff response for scale effects. The extent to which variability in vegetation cover influences hydrologic scale effects was determined by how it affected the hydrological processes. In this study, the difference between the vegetation cover rates was too large (from 20% to 70%), so large difference that we cannot be sure the key point of the effect of vegetation cover rate about the simulated runoff results.

The scale issue is becoming a focus of research on hydrological processes (Wang et al., 2001). Blöschl (2001) and Cerdan et al. (2004) suggested that we should focus on the dominant processes that control the hydrological response in different environments. In a subalpine watershed, there are many different dominant factors in hydrological processes in different seasons, but temperature is probably the main control factor that decides the recharge value for the melt water that is considered in a scaling model. Merz et al. (2006) indicated that the soil and land use characteristics had a low degree of impact on runoff processes. The results of this study, however, demonstrated that, at least in catchments with areas ranging from 0.41 km^2 to 80.5 km^2, land cover and its related soil characteristics (moisture and soil type) had an important influence on the runoff processes in this sub-alpine area. In the future, we should focus on how to quantitatively incorporate vegetation heterogeneity into the scaling models.

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Table 1. Characteristics of the four selected catchments.

Catchment Number	Elevation (m)	Drainage Area (km^2)	Forest Area (km^2)	Meadow Area (km^2)
1#	2920	80.5	15.5	15.0
2#	2960	7.47	5.51	1.80
3#	3060	1.05	0.95	0.10
4#	3100	0.41	0.31	0.09

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Table 2. Characteristic runoffs for the four selected catchments given for different seasons.

Catchment Number	Drainage Area (km^2)	Annual mean runoff (m^3/s)	Wet season runoff (m^3/s)	Dry season runoff (m^3/s)
1#	80.5	12.65	18.40	4.378
2#	7.47	0.620	0.956	0.300
3#	1.05	0.025	0.039	0.012
4#	0.41	0.003	0.005	0.001

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Table 3. The relationship of monthly scale runoff and temperature for four catchments given for dry season.

Catchment Number	Regression model (Q, runoff; T, Temperature)	R^2	P
1#	$Q = 4.2327e^{0.09097T}$	0.76	$< .001$
2#	$Q = 0.2894e^{0.1228T}$	0.84	$< .001$
3#	$Q = 0.0376e^{0.187T}$	0.57	$< .001$
4#	$Q = 0.003e^{0.2294T}$	0.69	$< .001$

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Table 4. Comparison of model performance in simulation runoff at monthly and daily scales for four selected catchments.

Catchment Number	Monthly mean runoff simulation									Daily mean runoff simulation								
	Dry season			Wet Season			Whole Year			Dry season			Wet Season			Whole Year		
	R^2	Nash	RE	R^2	Nash	RE	R^2	Nash	RE	R^2	Nash	RE	R^2	Nash	RE	R^2	Nash	RE
1#	0.78	0.74	0.1	0.68	0.65	0.16	0.89	0.88	0.15	0.80	0.80	0.04	0.72	0.64	0.06	0.90	0.88	0.05
2#	0.83	0.81	0.21	0.75	0.82	0.11	0.91	0.89	0.19	0.75	0.95	0.06	0.77	0.73	0.07	0.91	0.95	0.07
3#	0.56	0.74	0.18	0.61	0.71	0.14	0.80	0.81	0.13	0.73	0.63	0.36	0.52	0.62	0.11	0.89	0.85	0.24
4#	0.99	0.80	0.24	0.80	0.79	0.37	0.83	0.84	0.21	0.86	0.90	0.06	0.78	0.71	0.09	0.72	0.83	0.05

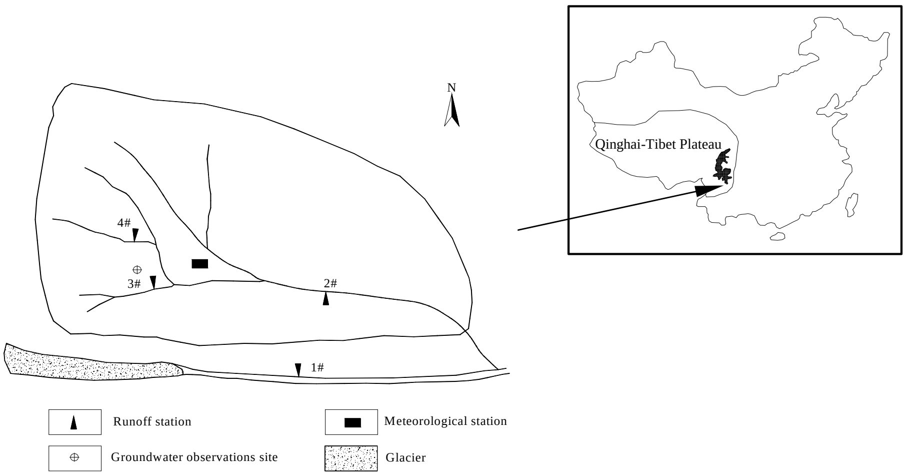

Fig. 1. The location of the research area and the river distribution.

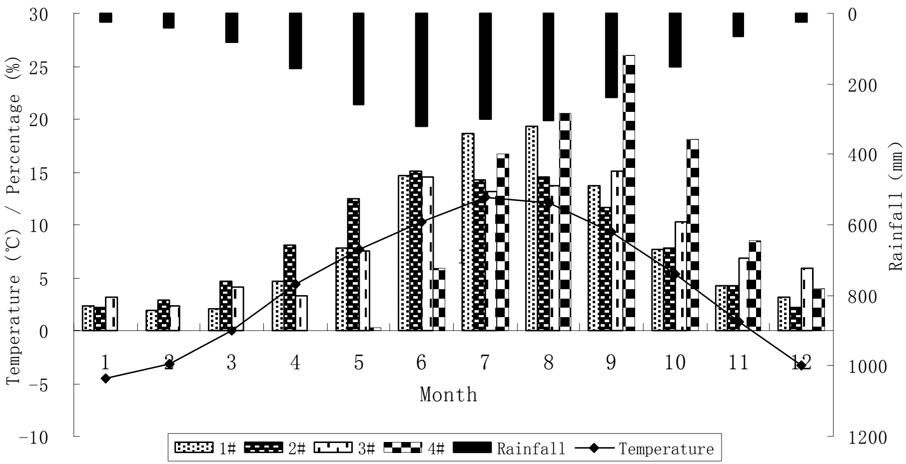

Fig. 2. The annual distributions of precipitation, temperature and runoff in four catchments. The runoff bars shows the percentage of monthly value account for the whole year. The runoff distributions of the four catchments were not equal.

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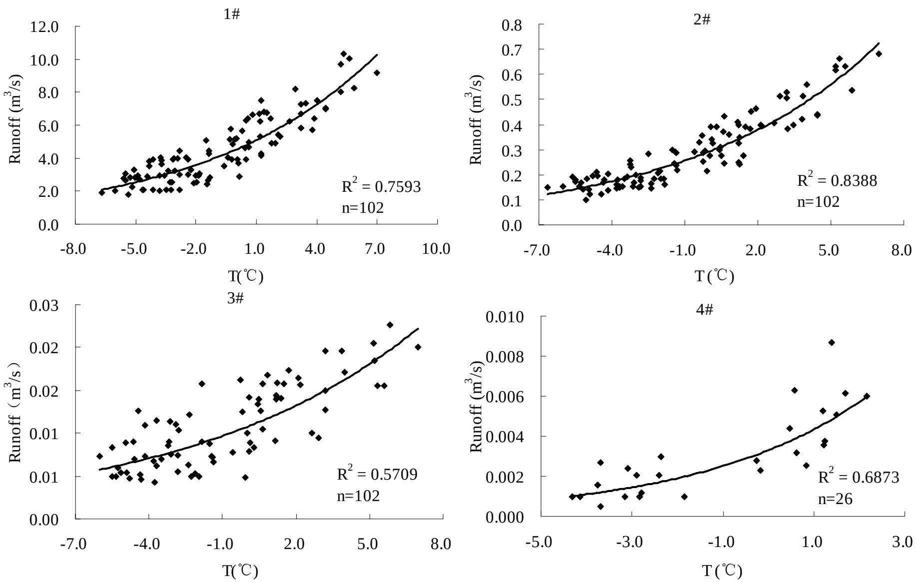

Fig. 3. The statistical relationship between the monthly scale runoff and temperature in the dry season. Runoff had a significant exponential relationship with temperature in the dry season.

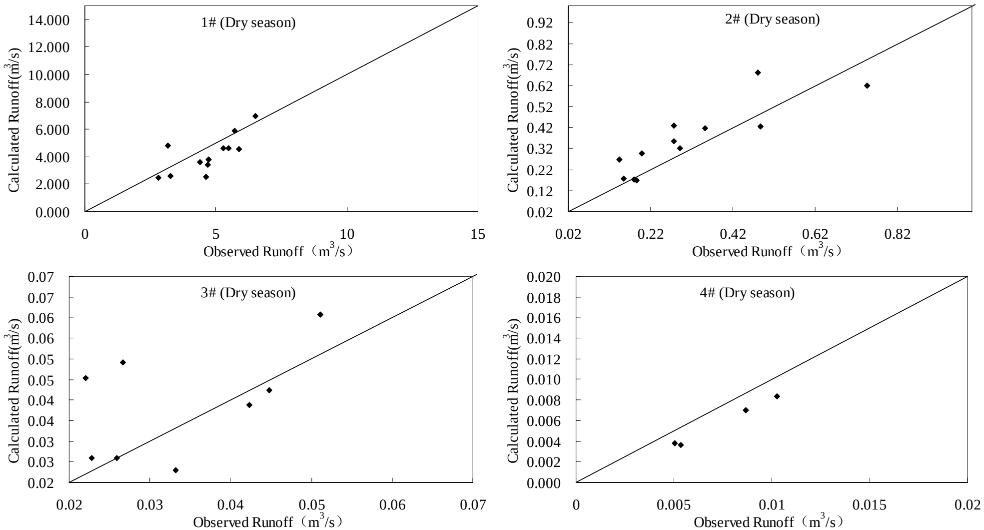

Fig. 4. Scatter plots of the observed and calculated monthly runoff for the four catchments in the dry season. The results showed a better consistency between the calculated and observed runoff values at all the gauging sites. Catchment 3# had the worst result, and the calculated runoff in catchments 1# and 4# were lower than the observed runoff. In general, the model gave a good simulation of the dry season.

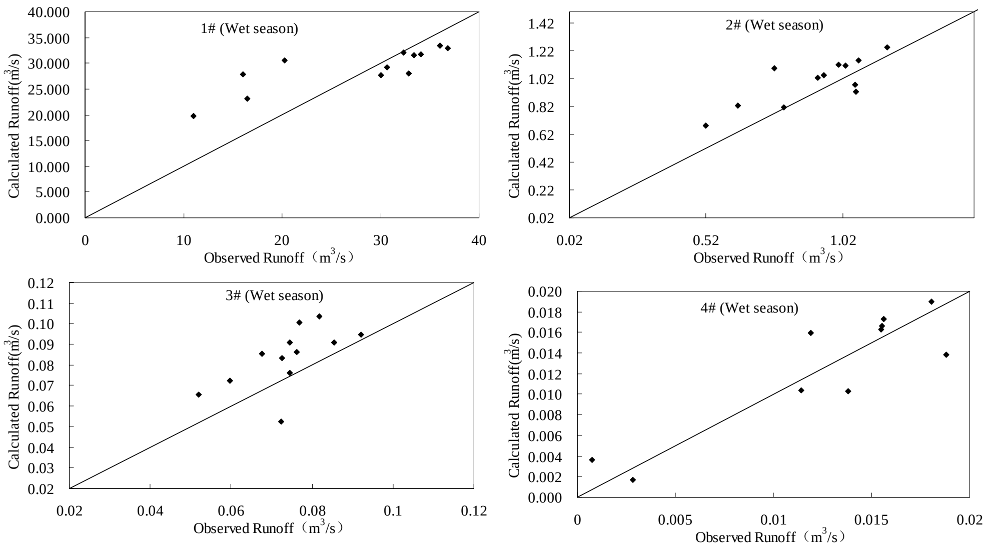

Fig. 5. Scatter plots of the observed and calculated monthly runoff for the four catchments in wet season. The calculated runoff was higher than the observed runoff except for the catchment 1#.

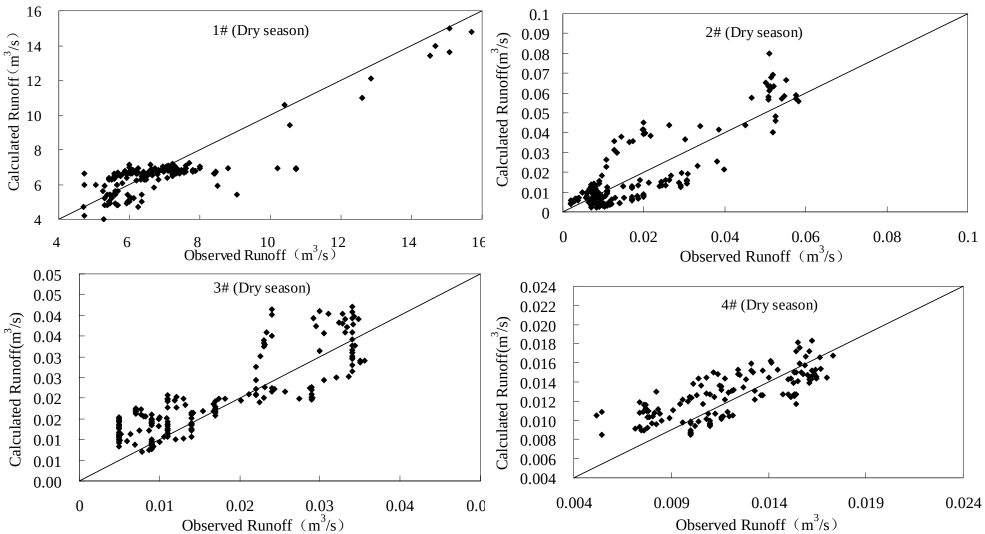

Fig. 6. Scatter plots of the observed and calculated daily runoff for the four catchments in the dry season.

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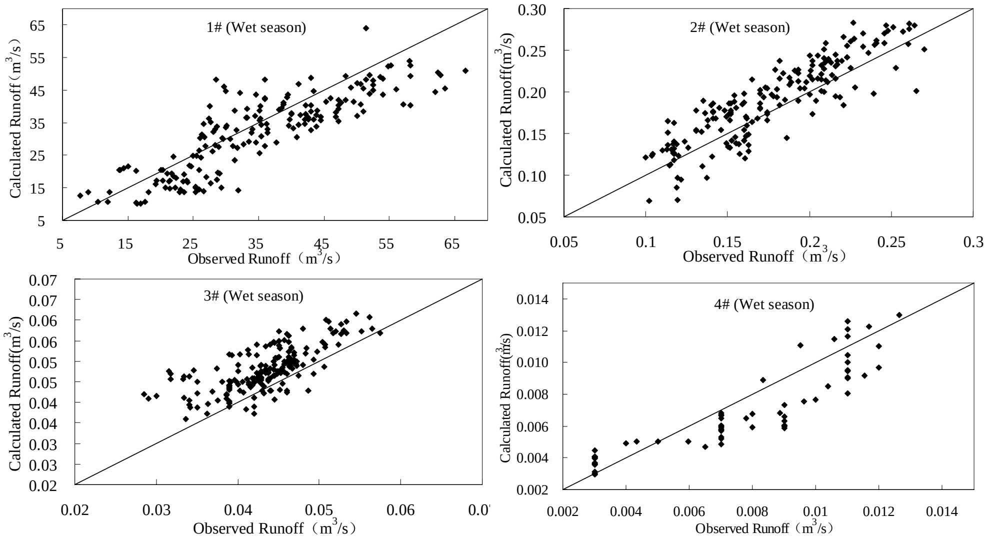

Fig. 7. Scatter plots of the observed and calculated daily runoff for the four catchments in wet season.

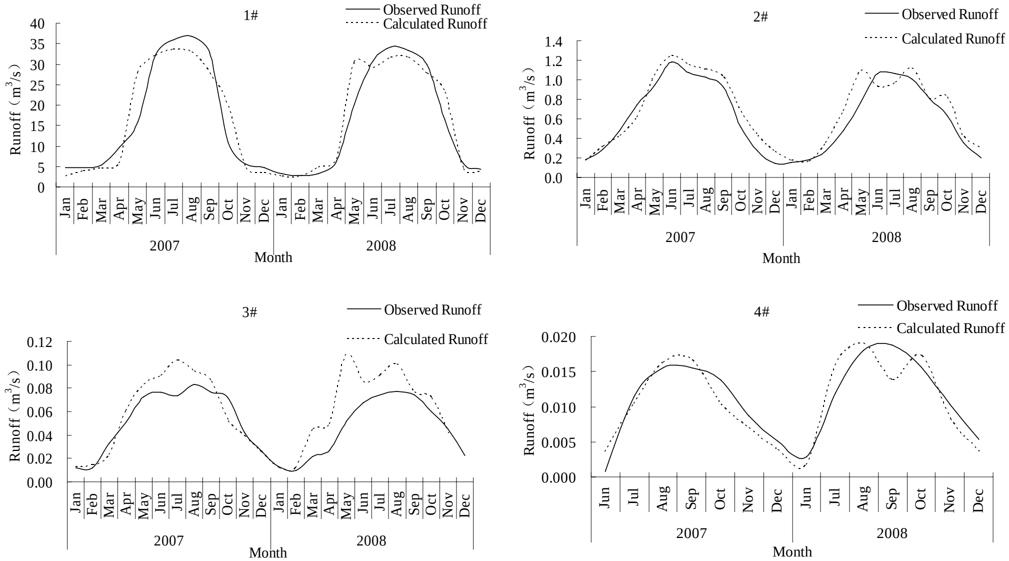

Fig. 8. Time series of the observed and calculated monthly runoff for 2 years in the four catchments.

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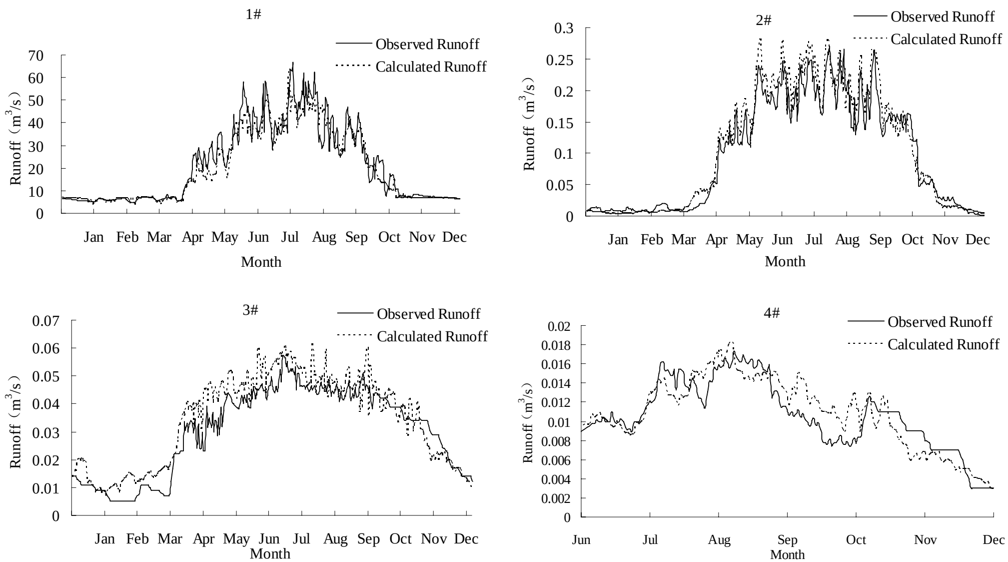

Fig. 9. Time series of the observed and calculated daily runoff for the four catchments.

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