44 *Cold Region Hydrology in a Changing Climate* (Proceedings of symposium H02 held during IUGG2011
in Melbourne, Australia, July 2011) (IAHS Publ. 346, 2011).

Temperature effects on seasonal streamflow and variation at different spatial scales in cold regions

GENXU WANG, GUANGSHENG LIU & LIN YUN

Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu 610041, China
wanggx@imde.ac.cn

Abstract A typical permafrost watershed and alpine cold forest watershed in the Qinghai-Tibet Plateau were selected to analyse the effects of soil and air temperature on runoff processes. The primary factors influencing surface runoff processes during different seasons were analysed by Principal Component Analysis (PCA), statistical regression, and the power spectrum fractal methods. The results indicated that regarding hydrological processes, different factors are dominant in different seasons, but temperature is probably the main controlling factor to be considered for runoff processes analysis in permafrost watersheds and cold alpine forest watersheds. Some statistic relationships illustrating the effect of temperature on runoff processes in different season and its variation at different spatial scales were developed in this study. These relationships provide a practical way for estimating the effects of temperature on runoff processes and the variation patterns at different spatial scales.

Key words runoff processes; spatio-temporal variability; temperature effects; cold region; Tibet

INTRODUCTION

Over the last decade, a number of studies have focused on diagnostic hydrological processes and their seasonal variation in arctic permafrost regions. Because of the presence of frozen soil, runoff in the arctic permafrost regions is commonly characterized by greater water yield and larger direct runoff ratios for both rain and snowmelt than those in the non-frozen or temperate regions (Hayashi *et al.*, 2003). McNamara *et al.* (1998) reported that the thawing active layer was an important factor influencing seasonal direct runoff in the Subarctic Wolf Creek watershed in Canada. However, in spite of significant progress in some separate hydrological processes (snow cover formation and snowmelt, freeze–thaw of the ground), the attempts to understand a detailed mechanism of hydrological cycle and runoff generation for these regions have had little success (Kuchment *et al.*, 2000; Hayashi *et al.*, 2003; Yamazaki *et al.*, 2006).

Recent catchment hydrological studies on scaling issues indicate that the scale effects vary significantly in different contexts and experimental methodologies. When monitoring surveys involve catchments larger than 1 km^2, the scale effect is even more obvious (Cerdan *et al.*, 2004). Based on studies of the scale issue in hydrology in the last decade, we conclude that there is no single unanimous scale effect that dominates all hydrological processes, and that the effect is either site- or context-specific, or dependent on the size of the monitored plots or catchments (Cerdan e*t al.*, 2004). One of the factors that make scaling difficult is the heterogeneity of catchments and the variability of hydrological processes. Therefore, it is necessary to study the scale issue in different catchments with different geographical and climate or vegetation conditions. Rainfall and runoff relationships have been widely used as a diagnostic tool for studies of runoff processes, as well as an important input parameter in hydrological design (Merz *et al.*, 2006). The scale effect on the rainfall–runoff relationship is crucial in hydrological studies. The objectives of the present study are: (1) to understand the effects of soil freeze–thaw variation on runoff processes in a permafrost watershed of QTP, and (2) to determine and quantify the nature of the scale effect for seasonal hydrological processes in the typical permafrost watershed.

STUDY SITE AND METHODOLOGY

The Zuomaokong watershed (127.63 km^2) and Hailuogou watershed (80.5 km^2), were selected as the study area (Fig. 1). The Zuomaokong watershed belongs to a permafrost region and the vegetation is dominated by *Kobresia pygmaea* C. B. Clarke and *Kobresia humilis* Serg (Wang *et*

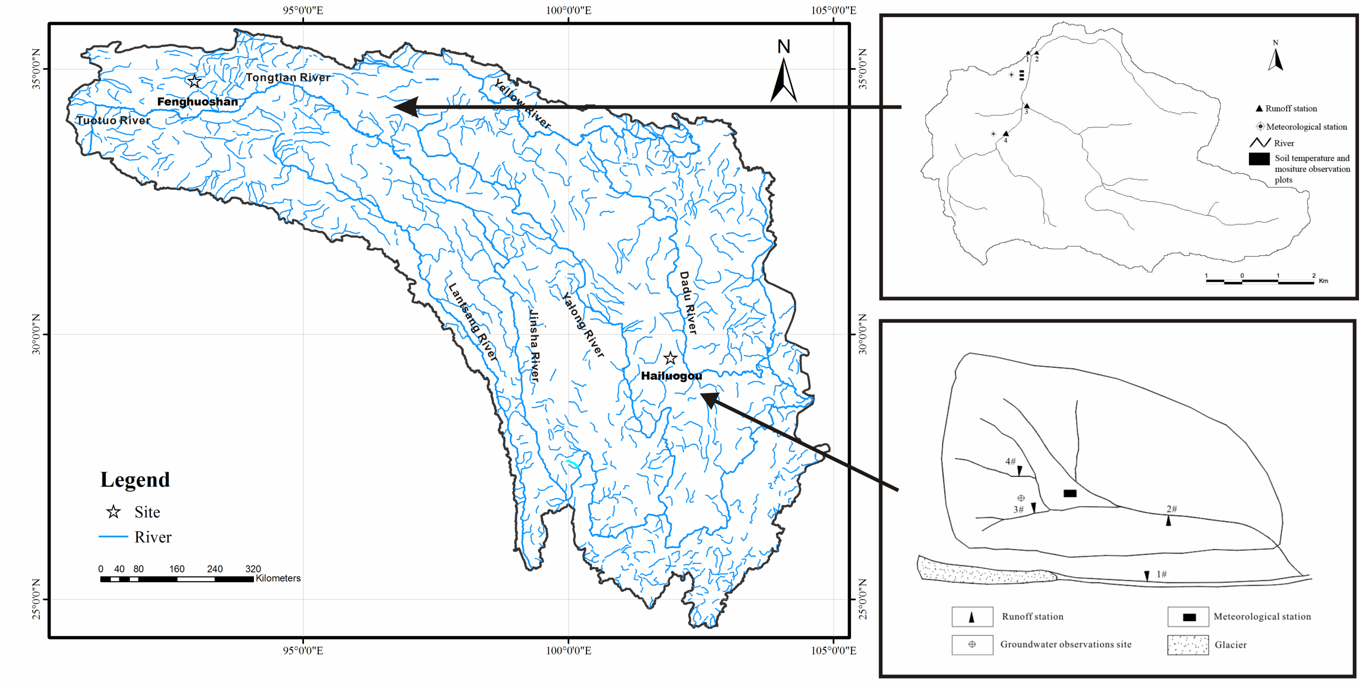

Fig. 1 The location of the research area and the river distribution.

al., 2001b; Zhou, 2001). The Hailuogou watershed is situated in an alpine forest region. *Abies* fabric forest is the main vegetation type in the subalpine area; it is a type of subalpine dark coniferous forest in southwestern China. There are four sub-catchments ranging from 0.41 km^2 to 80.5 km^2 in the research area.

In the Zuomaokong watershed, there were five runoff observation points (one at the outlet of the entire catchment, and the other four at the outlets of sub-basins). The discharge was measured at each site twice a day. Two soil temperature and moisture observation locations were located near the outlet section and the middle section of the watershed (Fig. 1). Soil moisture was determined by a frequency domain reflectometer (FDR) using a calibrated soil moisture sensor equipped with a Theta-probe (Holland, Eijkelamp Co.). Soil temperature was monitored using a thermal resistance sensor. In the Hailuogou watershed, the observation system at the Gongga Alpine Ecosystem Observation Station was established in 1988. The alpine hydrological observation system is one of the most important sections of the observation. This observation system contains two groundwater observation sites, one meteorological station, and four runoff observation sections. There are also additional instruments to observe air temperature and precipitation near the outlet of each sub-basin. At each runoff observation point, the discharge was measured by an automatic water level gauge placed at the outlet of each basin.

Fractal models have parameters that correlate features at one scale to those at all others, and as such they present an appealing methodology for linking processes across scales. To determine the scaling exponent for the transformation of rainfall–runoff dynamics across different spatial scales, annual runoff processes were separated into two periods based on the variation of runoff coefficients. One is from late June to early September, when the soil thawed out completely, and the runoff coefficients were lower. This is the summer season in the permafrost watershed and wet season in the alpine cold forest watershed. The other is the combined autumn, winter and spring seasons, when the soil freezes and thaws alternately. This is the cold season for the permafrost watershed and dry season in the alpine cold forest watershed. Principal component analysis (PCA) and statistical regression analysis were used to identify the main factors influencing the runoff formation and its seasonal variation.

RESULTS AND DISCUSSION

Impacts of temperature on seasonal runoff in permafrost region

In the permafrost watershed, our results revealed a significant linear relation ($R^2 \geq 0.45$, $P \leq 0.001$) between the discharge of the spring flood period and topsoil (0–20 cm) temperature (Fig. 2(a)). Surface runoff increased as the temperature of the active layer elevated. In particular, when the soil temperature was above 0.5°C, the runoff coefficient rose significantly. However, a weak exponential relation existed between air temperature and runoff (Fig. 2(b), $R^2 \leq 0.28$, $P = 0.01$). There was no clear relationship between precipitation and runoff, suggesting that precipitation had a weaker influence on runoff during the spring period. An exponential relation existed between the upper ground (0–60 cm) temperature, air temperature and autumn runoff (Fig. 3, $R^2 \geq 0.58$, $P \leq 0.001$). The autumn runoff declined exponentially with the decrease in soil and air temperature. Precipitation only played a minor role in spring flood runoff and autumn runoff, and exhibited a limited effect on direct runoff. Active soil thawing and freezing changed the soil water storage capacity, soil water infiltration capacity, and soil hydraulic conductivity, redistributing water in the soil profile. Consequently, seasonal variations in freeze–thaw of the active layer were the main cause for the seasonal changes in interflow and groundwater discharge, thus influencing the surface runoff process.

Air temperature and soil temperature at different depths of the active layer constituted the first component, with a level of influence on runoff of 41.3%, while soil moisture under the shallow active layer and spring precipitation were secondary factors, with a level of influence of 27.1%. Therefore, thawing processes of the active layer (including soil temperature and moisture) and air temperature were the primary factors influencing spring runoff. In autumn, the temperature and moisture of active layer and, air temperature explained over 82% of the runoff variation.

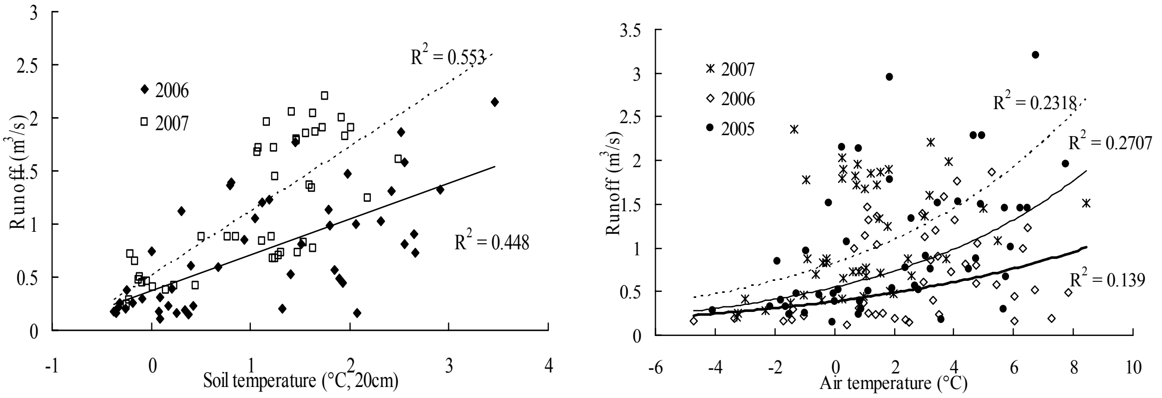

Fig. 2 Relationship between year-to-year spring flood-season river runoff (monthly) and soil temperature at 20 cm depth and air temperature, for a permafrost watershed on the Qinghai-Tibet plateau.

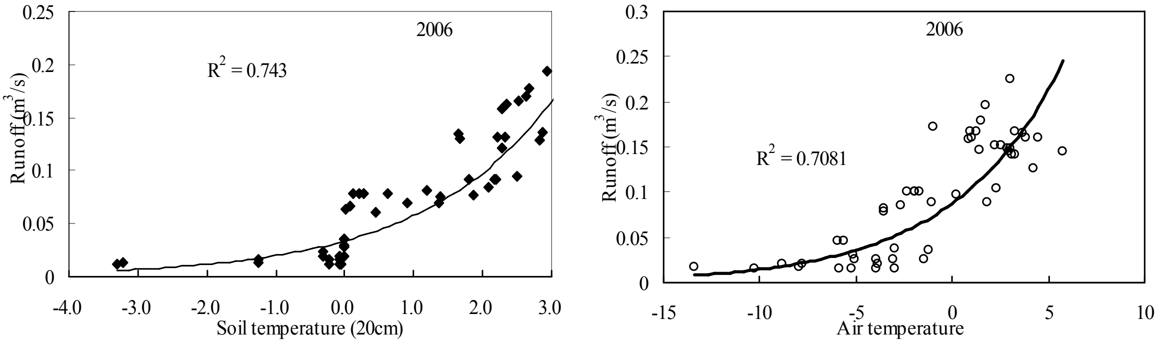

Fig. 3 Relationship between daily runoff and soil and air temperatures temperature of a permafrost watershed on the Qinghai-Tibet plateau during the autumn period.

Relationship between temperature and seasonal runoff in alpine forest region

Mean monthly temperature, rainfall, and runoff data for the dry season from 1990 to 2006 in the four sub-basins were collected and analysed. The primary factor affecting runoff in the dry season was the air and soil temperature. Air and soil temperature and runoff were significantly correlated, i.e. a significant exponential relationship for each gauging site during the dry season (Fig. 4, $R^2 \geq 0.57$, $P \leq 0.001$). In the alpine cold forest watershed, the dry season runoff increased exponentially with the soil and air temperature. Similar to in the permafrost watershed, when air temperature was above 0.5°C, the runoff coefficient rose significantly. Precipitation had a weak influence on runoff during the dry period ($R^2 \leq 0.21$, $P = 0.09$). Based on the PCA results, air temperature and surface soil temperature (0–20 cm) constituted the first component, with a level of influence on runoff of 56.7%. Soil moisture and precipitation were secondary factors, with a level of influence of 25.4%.

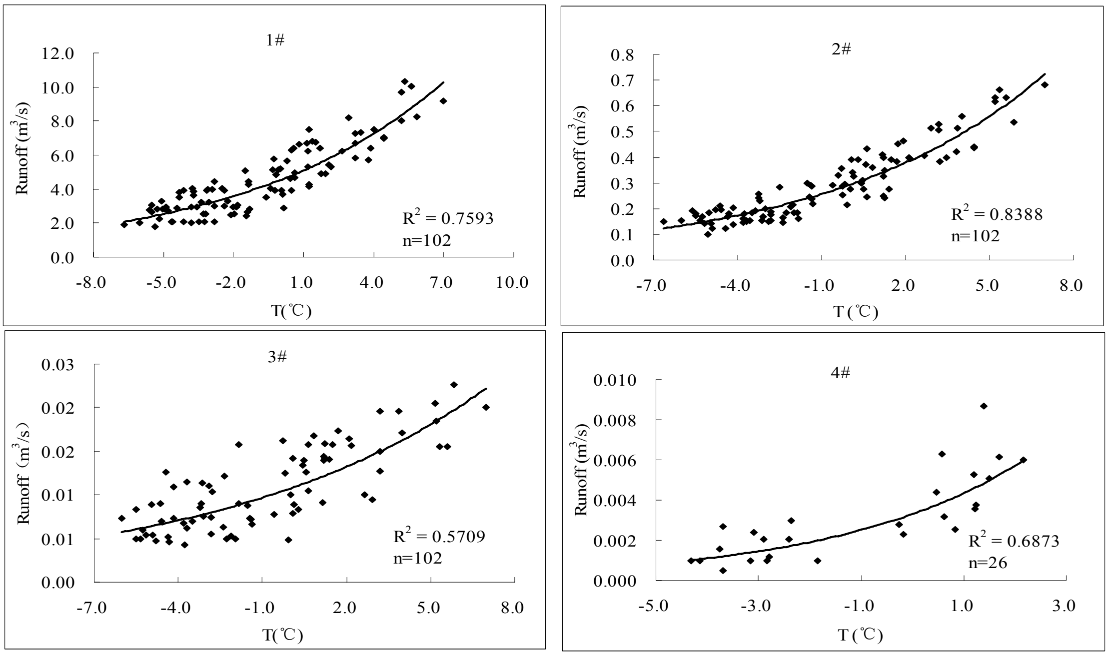

Fig. 4 The statistical relationship between the monthly scale runoff and temperature in the dry season in four sub-basin of the alpine forest watershed. Runoff had a significant exponential relationship with temperature in the dry season.

Variation of temperature effects on runoff at different spatial scales

1 Permafrost grassland watershed In the permafrost watershed, the daily mean runoff processes in the autumn and spring seasons had a significant power-function relation with the daily mean air temperature between September and October for different spatial scales ($R^2 > 0.71$, $P < 0.01$). The air temperature and precipitation are the controlling factors on runoff processes. The following equation was obtained for daily runoff processes in the autumn season, taking the two factors of air temperature and precipitation into account:

$$Q = 0.0296\mathrm{e}^{0.028k}\left(\mathrm{e}^{(0.0248\ln k + 0.0912)T_a}\right) + (0.0007k)P \qquad (1)$$

where k is the spatial scale (sub-basin area), P is precipitation (mm), and T is temperature (°C). Based on equation (1), the effects of temperature on the discharge of the basin and its variation at different spatial scales were estimated. In the autumn and spring seasons, air temperature had a significant influence on the soil freeze–thaw cycle, as mentioned above, which further affected the rainfall–runoff relationship. The correlation coefficient between the observed and simulated runoff using equation (1) was greater than 0.82, and the Nash value was greater than 0.67. In the permafrost watershed, there are many different dominant factors of hydrological processes in different seasons, but temperature is probably the main controlling factor to effect the variation of runoff at different spatial scales.

2 Alpine cold forest watershed Temperature and runoff were significantly correlated in an exponential relationship at the monthly scale for each gauging site during the dry season (Fig. 4). Based on this relationship, an exponential regression for each basin was built for the dry season, and the data series of spatial scales (e.g. catchment area) and temperature can be built. Then, the scale relationship was derived after the catchments area data were normalized. For the dry season, the scale relationship formula between temperature and runoff was as follows:

$$Q = (0.0532\ k - 0.0183\ )\mathrm{e}^{0.1891\ k^{(-0.1765\ )}T} \tag{2}$$

This relation was applied to all the catchments to test its general applicability for dry season runoff processes from 1 November 2007 to 30 April 2008, and the results are summarized in Fig. 4. The results are in agreement with the observations. In general, the results showed a significant scale effect between different catchments. For the wet season, a nonlinear regression was conducted for the runoff, rainfall, and temperature data was established as follows:

$$Q = 0.0007\,\mathrm{e}^{(0.01k)T} + (0.0004k - 0.0002)P + (0.001k^2 + 0.04k - 0.01) \tag{3}$$

Using the above relation (3), the wet season runoff processes in 2007 and 2008 were simulated for the different spatial-scale catchments. The results were also in agreement with the observations. It was inferred from equations (2) and (3) that temperature was the main controlling factor for runoff processes in the dry season. In the wet season, however, precipitation and temperature were coupling factors affecting the runoff. In different seasons, the effects of temperature on surface runoff varied with not only spatial scales, but the spatial pattern of precipitation. Based on equations (2) and (3), the effect of temperature and its variation on surface runoff were estimated. The R^2 between the simulated and observed runoff in different seasons and at different time scales were more than 0.75, and the Nash coefficients were more than 0.65. These results demonstrated the acceptability and vitality of the relationships, which suggest variations in temperature effects on runoff in different seasons across various spatial-scales (catchments).

CONCLUSION

In the two watersheds, air temperature is the primary factor controlling runoff processes in the dry season over the study area. In the wet season, precipitation, soil moisture and temperature were the primary factors to affect the seasonal discharge and its variation at different spatial scales. In the permafrost watershed, temperature and runoff showed an exponential relationship during the spring and autumn seasons, but not for the summer season. In the alpine forest watershed, similar to the permafrost watershed, there was a significant exponential relationship between air temperature and runoff during the dry season. However, in the wet season, there was a complex relationship among temperature, precipitation and discharge.

Overall, in the two watersheds, temperature is probably the main controlling factor for runoff process variation. A statistical relation illustrating the effect of temperature on runoff processes and its variation at different spatial scales was developed in this study. The scale issue is of central concern in hydrological processes for understanding the potential of upscaling or downscaling methodologies. In the permafrost watershed, many different factors are dominant of hydrological processes in different seasons, but temperature is probably the main controlling factor to consider in scaling models.

Acknowledgements This study were funded by the Natural Science Foundation of China (no. 40730634 and no. 40925002)) and the knowledge innovation project of the Chinese Academy of Sciences (KZCX2-YW-331).

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