Response of rock-fissure seepage to snowmelt in Mount Taihang slope-catchment, North China

Jiansheng Cao, Changming Liu and Wanjun Zhang

ABSTRACT

The complex physiographic and hydrogeological systems of mountain terrains facilitate intense rock-fissure seepages and multi-functional ecological interactions. As mountain eco-hydrological terrains are the common water sources of river basins across the globe, it is critical to build sufficient understanding into the hydrological processes in this unique ecosystem. This study analyzes infiltration and soil/rock-fissure seepage processes from a 65 mm snowfall/melt in November 2009 in the typical granitic gneiss slope catchment in the Taihang Mountains. The snowfall, snowmelt and melt-water processes are monitored using soil-water time-domain reflectometry (TDR) probes and tipping bucket flowmeters. The results suggest that snowmelt infiltration significantly influences soil/rock water seepage in the 0–100 cm soil depth of the slope-catchment. It is not only air temperature that influences snowmelt, but also snowmelt infiltration and rock-fissure seepage. Diurnal variations in rock-fissure seepage are in close correlation with air temperature ($R^2 > 0.7$). Temperature also varies with soil/rock water viscosity, which element in turn influences soil/rock water flow. Invariably, water dynamics in the study area is not only a critical water supply element for domestic, industrial and agricultural uses, but also for food security and social stability.

Key words | rock-fissure seepage, slope-catchment, snowmelt infiltration, Taihang Mountains, temperature

INTRODUCTION

Snow, a special surface cover in temperate regions, could profoundly influence thermal conditions on the land surface and in the atmosphere. Although it has high reflectivity and low thermal conductivity, snowmelt uniquely affects basin hydrological processes (Barnett et al. 1989). There exist extensive studies on snowmelt infiltration and runoff in permafrost and seasonally frozen regions (Miller 1978; Chamberlain & Gow 1979). Laboratory and field experiments (during winter/spring seasons) have been used to explain soil infiltration characteristics under frozen, thawing and melting conditions of snow; including infiltration resistance and permeability factors (Othman & Benson 1993; Dai et al. 2010; Chen et al. 2006).

In a pioneering study, Martinec et al. (1983) established a snowmelt runoff model (SRM) in the 2.65 km² watershed in France using semi-physical analysis. These and several other works have made more practical the simulation and prediction of snowmelt runoff in river basins. As SRM models remain scarce, the Martinec et al. (1983) SRM model is the only one recommended by the World Meteorological Organization (WMO 1986; Martinec et al. 1998; Gomez-Landesa & Rango 2002; Liu et al. 2006; Tekeli et al. 2005; Ma & Cheng 2003; Wang et al. 2001). The over-reliance on a single snowmelt simulation model indicates that snow hydrological processes are far from being fully understood.

In China, snow/frozen-land permeability studies have mainly focused on the Qinghai–Tibet Plateau and the permafrost/seasonally frozen grounds in the northeast and northwest mountain regions (Chang et al. 2005; Guo et al. 2005; Wang et al. 2007). Although snow-driven hydrological processes have been reported for North China (Wang & Ding 1995; Zhao et al. 2002; Sun & Zhao 2005), snowmelt infiltration processes such as rock-fissure seepage remain largely under-investigated. This study therefore analyzes snowmelt dynamics and rock-fissure seepage in Mount Taihang slope-catchment. Although this region has received the heaviest snowfall (=65 mm on average) in the North China Plain (NCP) since 1954, it remains largely under-studied in terms of snow seepage processes.
MATERIALS AND METHODS

Study area

The field-study was conducted in the Taihang Mountain Ecological Experimental Station (TMEES) of the Chinese Academy of Sciences. The station lies at an altitude of 350 m above mean sea level, longitude 114°15′50″ E and latitude N37°52′44″ N; which is also the mid-east slope region of Mount Taihang, Hebei Province (Figure 1). The landscape is moderately hilly, and is the intersection zone of east–west moisture and south–north thermal gradients.

The climate in the 0.026-km² slope-catchment is semi-arid continental monsoon, with annual average temperature of 13.0 °C, rainfall of 560 mm and evaporation of 1,200 mm. The dominant vegetation includes man-grown forests (mainly acacia) and shrubs (mainly jujube and vitex). The soil/weathered rock layers have dense distributions of roots of shrubs and forests. The slope-catchment is comprised mainly of a dual soil/rock system, with the soils sitting over the rocks and in vertical rock cleavages. The upper soil layer is thin (20–50 cm thick) and loosely mixed with gravel. The lower rock layer is gneiss regolith, with dense cracks and a thickness of 0.5–10 m; but can occasionally be 40 m thick (Cao et al. 2012; Han et al. 2012).

The rock fissures are complex with frequency and permeability decreasing with depth. The soil–rock interface is variable too with varying proportions of gravel. Because the weathered rock fissures are fairly developed, the basin average runoff coefficient is relatively small. However, underground seepage in the weathered gneiss rock fissures occurs throughout the year (Cao et al. 2012; Han et al. 2012).

Basic rock-fissure seepage concept

Rock-fissure seepage can be conceptualized as liquid flow in impervious parallel plates. In this sense, rock-fissure width is idealized as the separation distance between two parallel plates. Then for laminar flow conditions, average rate of liquid movement is calculated as follows:

\[ u = \frac{B^2}{12} \times \frac{\gamma}{\mu} \times J = \frac{B^2}{12} \times \frac{g}{v} \times J \]  

(1)

where \( u \) is the flow rate, \( B \) is the separation distance between the two plates, \( \mu = \rho \nu \) where \( \rho \) is liquid density and \( \nu \) is liquid dynamic viscosity, \( \gamma = \rho g \) where \( g \) is gravitational acceleration, and \( J \) is the hydraulic gradient.

Assuming equal fissure widths for a weathered rock-mass system, seepage velocity along fissure intersections is calculated as follows:

\[ \nu = nu = \frac{nB^2}{12} \times \frac{\gamma}{\mu} \times J = \frac{nB^2}{12} \times \frac{g}{v} \times J \]  

(2)

where \( \nu \) is seepage velocity, \( n \) is fissure intersection number, and other variables are as defined in Equation (1).

Experimental design

Rock-fissure flow

An underground tank-enclosure was built at the main outlet of the slope-catchment and a sump buried underneath it to allow smooth outflow of the rock-fissure seepage. A 32-mm PVC pipe connected the tank-enclosure and the sump. Because of the generally small rock-fissure flow in the region (<500 l/h), common flow-gauge equipment and/or methods (e.g. water meter or weir flow method) could not be used to accurately monitor flow dynamics in the slope-catchment.

To overcome this obstacle, the tipping bucket flow meter was used. The meter uses volumetric principles to monitor continuous seepage flow. It is therefore appropriate for
monitoring rock-fissure seepage discharge under non-pressure, low-head and low-flow rate conditions. The main components of the tipping bucket flow meter include a flow sensor (symmetric double-dump), a pulse generator (magnet and reed switch) and a pulse recorder (CR10X data acquisition device, Campbell Scientific, USA). The pulse recorder resolution was 200 ml, the flow range was 0–600 l/h and sampling time interval was 20 min.

Groundwater dynamics

The CS615 Water Content Reflectometer (Campbell Scientific, USA) was used to determine groundwater dynamics in the slope-catchment. The reflectometer, which was connected to CR10X for automatic data acquisition, uses time domain reflectometry (TDR) to gauge groundwater dynamics. To insert the CS615 reflectometer into the soil, the slope gradient was vertically cut open and the CS615 reflectometer probes horizontally inserted into the soil/rock system at different depths. The probes were inserted into the soil layer at depths of 10, 20 and 30 cm; at a soil/rock interface depth of 50 cm; and then into the rock layer at depths of 80 and 100 cm. All the probes were sampled every 20 min.

Meteorological data

The Dynamet Automatic Weather Station (Dynamax, USA) was used to monitor meteorological conditions in the slope-catchment, including wind speed, wind direction, solar radiation, air temperature, soil temperature, precipitation and relative humidity. The sampling interval of the meteorological variables was also 20 min.

Snowfall/melt characteristics

The snowfall event investigated in this study started at 0730 hours on 10 November 2009 (which was day 314 of the year) and ended at 0600 hours on 11 November 2009 (which was day 315 of the year). It was the largest snowfall since 1954 (49 cm), with a snowmelt water equivalent of 65 mm. The snowmelt lasted for 21 days and ended on day 336 of the year, which was on 2 December 2009.

RESULTS AND DISCUSSIONS

Soil/rock response to snowmelt

Figure 2 depicts soil/rock water dynamics driven by snowmelt infiltration at different depths. As shown in the figure, there are obvious different responses of soil/rock water at the 30, 60 and 100 cm depths to snowmelt infiltration. For especially the 30 cm depth, soil/rock water increases in a step-wise trend. The first step, which lasts for the period from 1240 hours on 11 November 2009 (day 315 of the year) to 0940 hours on 16 November 2009 (day 320 of the year), represents a percentage water content increase of 35.8%. The second step, which lasts from 1940 hours on 20 November 2009 (day 324 of the year) to 2020 hours on 25 November 2009 (day 329 of the year), represents a percentage water content increase of 35.8%. The second step, which lasts from 1940 hours on 20 November 2009 (day 324 of the year) to 2020 hours on 25 November 2009 (day 329 of the year), represents a percentage water content increase of 35.8%. Following a moderate drop after the second step, the water content rebounds in

Figure 2 | Plots of the response of soil/rock water to snowmelt infiltration at different depths below land surface for the winter of 2009.
the third time step; lasting for a much shorter period from 1400 hours on 29 November 2009 (day 333 of the year) to 2200 on 30 November 2009 (day 334 of the year). The percentage water content rapidly decreases after that period, dropping to the low of 36.7% at 1300 hours on 6 December 2009 (day 340 of the year).

The water content at the 60 cm depth tracks a different trend altogether. It increases for the period from 2040 hours on 15 November 2009 (day 319 of the year) and reaches the maximum of 39.3% at 0900 hours on 3 December 2009 (day 337 of the year). It then decreases after that to 38.9% at 1300 hours on 6 December 2009 (day 340 of the year). Also, water content at the 100 cm depth gradually increases for the period from 0500 hours on 24 November 2009 (day 328 of the year) and reaches the maximum of 39.8% at 1300 hours on 6 December 2009 (day 340 of the year). This suggests that snowmelt infiltration reaches or even exceeds 100 cm soil depth in the Mount Taihang slope-catchment. It also suggests that the effects of other factors (e.g. temperature, vegetation and evapotranspiration) on snowmelt infiltration in the region decrease with increasing soil depth.

**Rock-fissure seepage response to snowmelt**

**Figure 3** depicts rock-fissure seepage response to snowmelt recharge for the period from November 10 (day 314 of the year) and December 2 (day 336 of the year) 2009 at 20 min sampling intervals. As shown in the figure, an initial increase in the rock-fissure seepage is followed by a steep decline. Then the seepage flow rises again from the low of 725 ml/min on 10 November 2009 (day 314 of the year) to the maximum of 828 ml/min at 1400 hours on 19 November 2009 (day 323 of the year). It again gradually decreases to the low of 750 ml/min at the end of the snowfall on 2 December 2009 (which is day 336 of the year).

Diurnal variations in the rock-fissure seepage flow depict high amplitude ranges at the peak of snowmelt and low amplitude ranges at the start/end of snowmelt. This suggests that snowmelt-water infiltration in the highly weathered rock-masses facilitates rock-fissure seepage in the slope-catchment. The maximal snow-water infiltration and hence seepage flow occur at the early stage of snowmelt (on 19 November 2009). This trend keeps fluctuating throughout the snowmelt period, suggesting that some other factors influence snowmelt and the related hydrological processes in the region.

The characteristics of rock-fissure seepage, air temperature and snowmelt infiltration are explored by analyzing average daily seepage and temperature trends. The specific period 14–15 November 2009 (days 318–319 of the year) was selected randomly from the whole snowmelt stage and the results are plotted in **Figure 4**. There are obvious diurnal variations in rock-fissure seepage flow with the maximum value at 1230–1330 hours and minimum at 0230 hours. There is an overall increase in rock-fissure seepage flow from 0230 through 1230 hours, and an overall decrease from 1330 through 0220 hours. The dynamics of rock-fissure seepage is generally in sync with that of air temperature, and a similar relationship is repeated at other times. The underground seepage in the weathered
gneiss rock fissures occurs throughout the year and the daily fluctuation trend is not changed during the snowmelt period.

Correlation plots between rock-fissure seepage and air temperature are depicted in Figure 5 respectively for days 14 and 15 of November 2009. The plots are completed with linear regression lines, equations \((n = 72)\) and coefficient of determination \((R^2)\) values. As shown in Figure 5, \(R^2\) for both plots is greater than 0.74. A similar relationship is repeated at other times, and this further confirms that the rock-fissure seepage is closely related with air temperature in the Mount Taihang hill slope catchment.

**Formation mechanism of diurnal variations in seepage**

To make the formation mechanism of diurnal variations in seepage clear, Equations (1 and 2) can be used under standard atmospheric pressure conditions to plot the link between soil/rock water viscosity and temperature.
in the slope-catchment. With increasing temperatures, soil/rock water viscosity coefficient also gradually decreases (Kaye & Laby 1995). This suggests that the formation mechanism of diurnal variations in rock-fissure seepage is that the change of flow water viscosity is dependent on variation of temperature in the study area. When temperature falls, flow water viscosity rises, with a decrease in the corresponding seepage velocity. Under similar conditions, the reverse holds true when temperature rises.

CONCLUSIONS

The Taihang Mountain ecology provides the needed conditions for headwater catchment in North China. It is, however, a transitional zone that is ecologically fragile and with severe water shortage due to rapid economic development. Although snowfall in the region accounts for a small fraction of the precipitation, its time of occurrence (which is in the winter season when the lands are bare) induces groundwater recharge in the plain region.

This study suggests that snow-driven rock-fissure seepage is significantly influenced by diurnal variations in daily temperature. Temperature also influences soil/rock water viscosity, which in turn influences seepage flow. Warming climatic conditions may not only facilitate snowmelt, but also melt-water infiltration and groundwater recharge in the piedmont corridors. However, rising temperatures due to global warming could also limit the incidence of winter snowfall and soil/rock water availability in the mountains. This may affect vegetation and the wider ecosystem. Irrespectively, however, adequate understanding of the hydrological processes in the region is critical for domestic, industrial and agricultural water supply. It is also critical for food security and social stability in the region.

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