THE RELATIONSHIP BETWEEN PREFERENTIAL FLOW IN SNOW COVER AND WEATHER CONDITIONS

Satoru Yamaguchi* Hiroyuki Hirashima* Atsushi Sato* Satoru Adachi*
*Snow and Ice Research Center, National Research Institute for Earth Science and Disaster Prevention (NIED), Nagaoka, Niigata, Japan

ABSTRACT: The accurate description of water movement through snow cover is essential for improving the forecast of full depth avalanches; this forecast is closely related to the amount of water discharge from the bottom of snow cover. Water penetrations into snow cover are classified to two categories: uniform penetration and preferential penetration through water pass. Therefore, one dimensional model for water movement in snow cover is inadequate for simulating realistic water behavior in snow cover. Snow and Ice Research Center, NIED, has a multi-lysimeter (3m × 3m area) consisting of nine small lysimeters with an area of 1m × 1m. Using the multi-lysimeter, we have measured the distribution of water discharge from the snow cover bottom since 2006. The measured data indicate that a strong heterogeneous distribution of water discharge, which is obtained from the large difference between discharges at each small lysimeter, sometimes occurred in the melt season. Such a heterogeneous distribution of water discharge is attributed to the preferential flow of water through the water pass due to horizontal water movement in the snow cover. The analyses using meteorological data indicate that the appearance of heterogeneous distribution of water discharge is closely related to the amount of water input into snow cover; this input water is obtained from melt-water and rain. When water input increases, strong heterogeneous distribution of water discharge occurs. This result provides beneficial information for understanding the mechanism of horizontal water movement in snow cover.

1. INTRODUCTION

Full-depth avalanches are mainly triggered by water reaching the bottom layer of the snow cover. Moreover, rain falling on snow is a major cause of mid-winter avalanches in maritime climates (e.g., Wilson, 1986; Conway et al., 1988; Heywood, 1988; Convey and Raymond, 1993; Osterhuber and Kattelman, 1998). In some cases, rain on snow may also produce severe runoff and erosion by generating intense and damaging floods (e.g., Harr, 1981; Kattelmann, 1997; Marks et al., 1998). Therefore, an accurate description of water movement through snow cover is essential for improving the forecast of wet-snow disasters. To improve the simulation of water movement through snow cover in a numerical snow cover model (SNOWPACK) (Bartelt and Lehning, 2002; Lehning et al., 2002a; Lehning et al., 2002b), HIrashima et al (2010) adopted the idea of unsaturated hydraulic conductivity of snow based on cold-room experiments (Yamaguchi et al., 2010) and succeeded in reproducing the appearance and disappearance of layers with a high water content in seasonal snow. Although these studies have contributed to our understanding of the mechanism of water movement in snow and improved the modeling of uniform penetration into snow cover, penetrations into natural snow cover are generally separated into two categories: uniform penetration and preferential penetration through water pass resulting from horizontal water movement. Therefore, a one-dimensional water-movement model is inadequate for simulating realistic water

*Corresponding author address:
Satoru Yamaguchi, Snow and Ice Research center, National Research Institute for Earth Science and Disaster Prevention, Suyoshi-machi, Nagaoka, Niigata, Japan 940-0821;
tel: +81-258-35-7520; fax:+81-258-35-0020; email: yamasan@bosai.go.jp

behavior in snow cover due to the inability to account for horizontal water movement. To expand a one-dimensional water movement model to simulate multidimensional water movement in snow cover, it is necessary to understand conditions that generate preferential penetration through water pass. The purpose of this study was to examine the relationship between preferential penetration flow in snow cover and weather conditions using field measurement.

2. METHODS

We used data measured at Snow and Ice Research Center (SIRC), NIED (37°25´N; 138°53´E; 97 m a.s.l.), where mean daily air temperature during the winter season (Dec–Feb) is higher than 2°C and deposited snow is wet due to the formation and percolation of melt water throughout the winter season. The maximum snow height in the winter is typically greater than 1.5 m. In addition to measuring basic hourly meteorological data (e.g., temperature, humidity, wind speed, precipitation, snow height and weight), from 2006 onward, SIRC has also measured the distribution of water discharged from the bottom layer of snow cover using a multi-lysimeter (3 × 3 m area) consisting of nine small lysimeters with an area of 1 × 1 m (Fig. 1) .

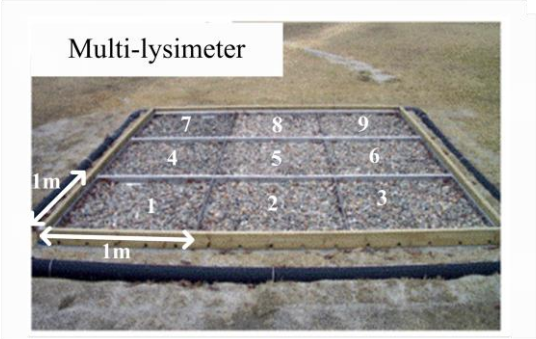


Fig.1 Multi-lysimeters at SIRC.
The white number is the number for each lysimeter.

3. RESULTS AND DISCUSSION

3.1 *Heterogeneous distribution of water discharge*

Figure 2 shows the data from daily measurements by the multi-lysimeter from Dec 2010 to Apr. 2011. The data indicated that a strongly heterogeneous distribution of water discharge sometimes occurred during periods of snow melting due to the large differences between discharges at the various small lysimeters. Because surface undulation on the multi-lysimeter, resulting from heterogeneous distribution of surface melting, was not observed during the study period, we considered that such a strongly heterogeneous distribution of water discharge could be attributed to the preferential flow of water from the water pass due to horizontal

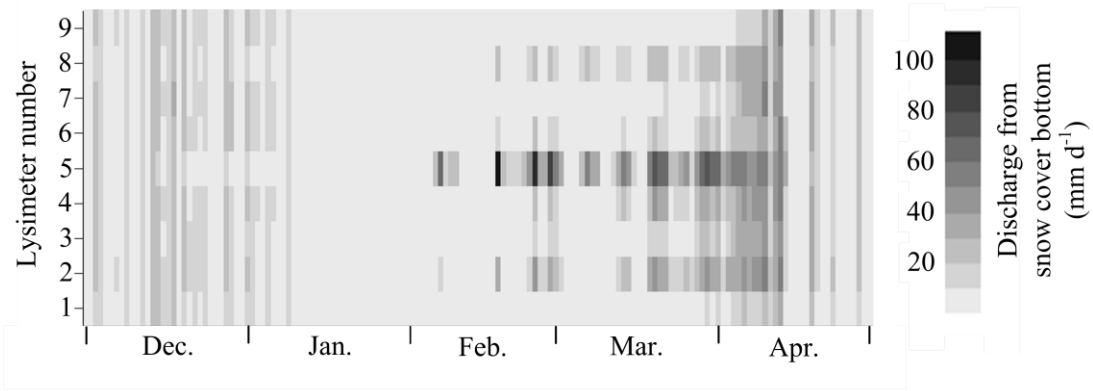


Fig.2 Daily measurement results from each multi-lysimeter at SIRC (Dec 2010 to Apr 2011).
The lysimeter number corresponds to the number in Fig.1.

water movement in the snow cover. We have introduced the idea of a water discharge deviation (δW_i) defined by the following equation:

$$\delta W_i = W_i - W_{ave}. \quad (1)$$

Here, W_i is water discharge from No.*i* lysimeter, and W_{ave} is the average water discharge from the nine lysimeters. We adopted the largest value of δW_i from the nine lysimeters (δW_{max}) as an indicator of the strength of the heterogeneity of the distribution of water discharge. We focused on seven periods in which a remarkably large δW_{max} occurred (6-8 Feb, 17- 9 Feb, 24-26 Feb, 27 Feb-1 Mar, 13-15 Mar, 19-23 Mar, 28-31 Mar) to examine the relationship between a strongly heterogeneous distribution of water discharge and weather conditions.

3.2 *Weather conditions during the occurrence of a heterogeneous distribution of water discharge*

Figure 3 shows the hourly temperature (°C), precipitation amount (mm h^{-1}), and δW_{max} during two periods when a large δW_{max} was observed (17-19 Feb, and 24-26 Feb). Both periods had high temperatures and rainfall, which would have

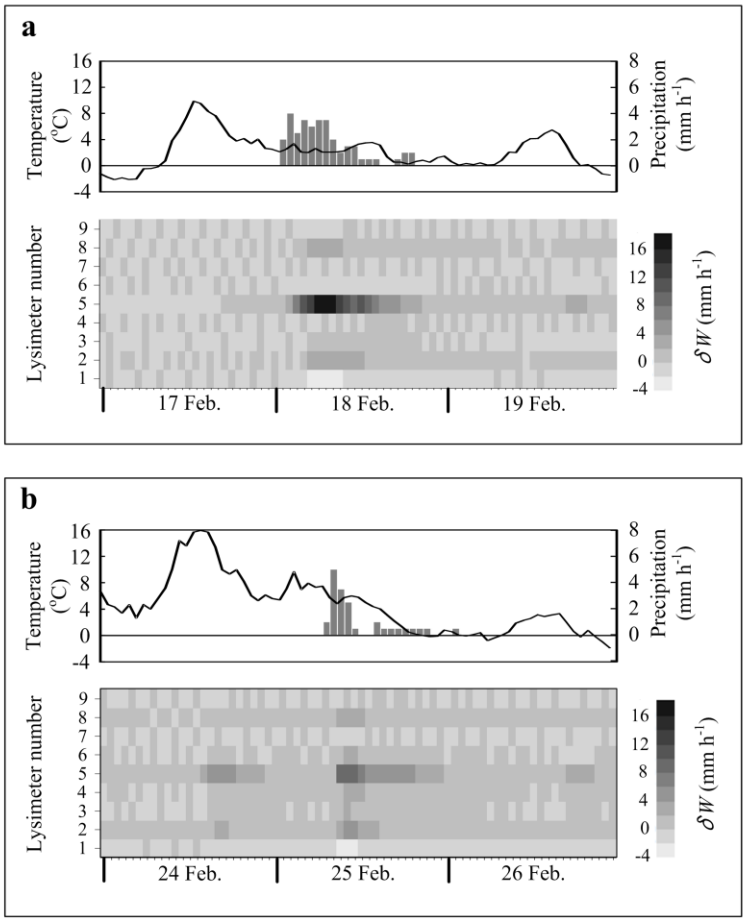


Fig.3 The relationship between weather conditions and δW_{max}.
a: Data for the period from 17 Feb to 19 Feb 2011.
b: Data for the period from 24 Feb to 26 Feb 2011.
Black solid lines indicate temperature, and gray bars indicate precipitation.

generated a large water input into the snow prior to the occurrence of the large δW_{max}. The same trend was apparent for the remaining periods. From these results, we concluded that a large water input into snow cover leads to a heterogeneous distribution of water discharge, which results from the preferential flow of water from the water pass due to horizontal water movement in the snow cover.

3.3 The relationship between water input and a heterogeneous distribution of water discharge

To estimate the water input due to snowmelt, we introduced the "positive degree hour", which is based on the same concept as the "positive degree day", i.e., if the hourly temperature (T_h) is positive, then hourly snowmelt in the form of liquid water (M: mm h^{-1}) is calculated from the following equation:

$$M = K \times T_h, \quad (2)$$

where, K is the "positive degree hour factor" which was assigned the value of 0.17 mm $°C^{-1}$ h^{-1} by dividing the standard value of the positive-degree-day factor in this region by 24 hours. Thus the total hourly water input into snow cover (W_{input}) is considered to be the sum of hourly precipitation and snowmelt.

It is likely that the sum of W_{input} over several hours (ΣW_{input}) affects the behavior of water in snow cover because sometimes it takes several hours for water penetration into snow cover to occur. Hence, we calculated the correlation coefficient (R) between δW_{max} and ΣW_{input} for periods of 1 to 10 hours. The value of R increased as the hours were integrated up to 6 hours, after which it deceased up to 10 hours. Therefore, we considered that the most effective parameterization of water input into snow cover is the sum of 6 hours' water input (ΣW_{input_6h}) when modeling the strength of the heterogeneous distribution of water discharge.

Figure 4 shows the relationship between ΣWi_{nput_6h} and δW_{max}. When ΣW_{input_6h} is small, the ratio of the change in δW_{max} against the change in ΣW_{input_6h} ($d\delta W_{max}$) is small, but $d\delta W_{max}$ becomes larger with an increase of ΣW_{input_6h}. These results indicate that the strength of the heterogeneity of the distribution of water discharge is controlled by the amount of water input into snow cover. Using this relationship, we modeled δW_{max} as a quadratic function of ΣW_{input_6h}.

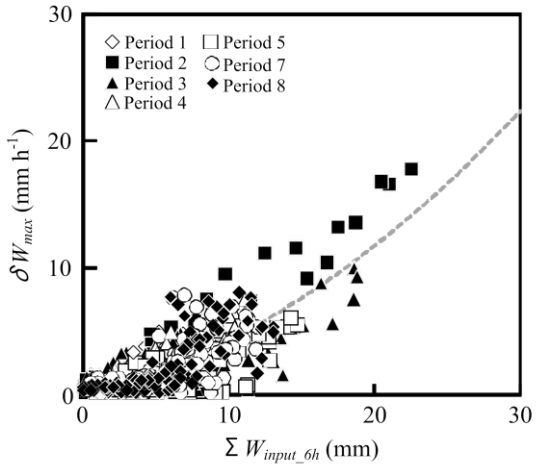


Fig.4 The relationship between ΣW_{input_6h} and δW_{max}.
Gray broken lines are a curve fitted by quadratic function.
Period 1: 6-8 Feb 2011
Period 2: 17-19 Feb 2011
Period 3: 24-26 Feb 2011
Period 4: 27 Feb-2 Mar 2011
Period 5: 13-15 Mar 2011
Period 6: 19-23 Mar 2011
Period 7: 28-31 Mar 2011

4. CONCLUSIONS

We measured the heterogeneity of the distributions of water discharge from the bottom layer of snow cover, which could be attributed to the preferential flow of water from the water pass due to horizontal water movement in the snow cover, using a multi-lysimeter (3 × 3 m area) consisting of nine small lysimeters with an area of 1 × 1 m each at the SIRC. We then analyzed the data alongside the corresponding meteorological data. Our study indicated that the appearance of a heterogeneous distribution of water discharge was closely related to the amount of water input, including snowmelt

and rainfall, into snow cover. When the water input increased, a strongly heterogeneous distribution of water discharge occurred. This result provides useful information for understanding the mechanism of horizontal water movement in snow cover.

5. REFERENCESS

Bartelt, P. B. and Lehning, M., 2002. A physical SNOWPACK model for the Swiss avalanche warning: Part I. Numerical model. *Cold Reg. Sci. Technol*. **35(3)**, 123-145.

Conway, H., Breyfogle, S., and Wilbour, C., 1988. Observations relationg to wet snow stability. *Proc. Int. Snow Sci. Workshop, Whistler, BC*. 211-222.

Convway, H. and Raymond, C., 1993. Snow stability during rain. *J. Glaciol.*, **39,** 635-642.

Harr, R. D., 1981. Some characteristics and consequeices of snowmelt during rainfall in Western Oregon. *J. Hydrol.*, **53**, 277-304.

Heywood, L., 1998. Rain on snow avalanche event – some observations. *Proc. Int. Snow Sci. Workshop, Whistler, BC. ,* 125-136.

Hirashima, H., Yamguchi, S., Sato, A., Lehning M., 2010. Numerical modeling of liquid water movement through layered snow based on new measurements of the water retention curve. *Cold Reg. Sci. Technol*., **64(2)**. 94-103.

Kattelmann, R., 1997. Flooding from rain-on-snow events in the Sierra Nevada. *Destructive water: Water-Caused Natural Disasters, their abatement and control.* George H. Leavesley, Harry F. Lins, Franz Nobilis, Randolph S. Parker, Verne R. Schneider, and Frans H. M. van den Ve (ed.). IAHS Publication, **239**, 59-65.

Lehning, M., Bartelt, P. B., Brown B., Fierz, C., Satyawali, P.. 2002a. A physical SNOWPACK model for the Swiss avalanche warning: Part II. Snow Microstructure. *Cold Reg. Sci. Technol*. **35**(3), 147-167.

Lehning, M., Bartelt, P. B. Brown, B., Fierz. C., 2002b. A physical SNOWPACK model for the Swiss avalanche warning: Part III. Meteorological forcing, thin layer formation and evaluation. *Cold Reg. Sci. Technol*. **35**(3), 169-184.

Marks, D., Kimball, J., Tnigey, D., and Link, T., 1998. The sensitivity of snowmelt processes to climate conditions and forecast cover during rain-on –snow: A case study of the 1996 Pacific Northwest flood. *Hydrol. Process,* **12**, 1569-1587.

Osterhuber, R. and Kattelmann, R., 1998. Warm storms associated with avalanche hazard in the Sierra Nevada. *Proc. Int. Snow Sci. Workshop, Sunriver, OR.,* 526-533.

Yamaguchi, S., Katsushima, T., Sato, A., Kumakura, T., 2010. Water retention curve of snow with different grain sizes. *Cold Reg. Sci. Technol*., **64(2)**. 87-93.

Wilson, N., 1986. A widespread cycle of unususal avalanche events. *Proc. Int. Snow Scie. Workshop*, *Snowbird, UT.,* 153-1