APPLICATION OF A MULTI-DIMENSIONAL WATER TRANSPORT MODEL TO REPRODUCE THE TEMPORAL CHANGE OF RUNOFF AMOUNT

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ABSTRACT: In this study, multiple simulations were performed in Nagaoka, Japan, a warm-snow region, by combining the numerical snowpack model, SNOWPACK, and a multi-dimensional water transport model. The SNOWPACK simulation was first performed in order to obtain the layer structure, snow density, grain size, and water content of the snow. Secondly, changes due to rain and snowmelt were extracted from the output of SNOWPACK. For each event, water transport simulations were performed using the water transport model. Within the water transport simulation, the initial snow parameters and the amount of snowmelt were taken from the output results of SNOWPACK. The multi-dimensional simulation showed different characteristics from the one-dimensional simulation, as the liquid water infiltrated the dry snow layer. Simulated time series of runoff amounts was compared with the lysimeter data. Although using the multi-dimensional simulation, as opposed to the single-dimensional simulation, mitigated the delay of the simulated runoff, it proved insufficient because of the effect of preferential flow. The results suggest that it is necessary to consider the densification of snow and the formation of snow dimples.

KEYWORDS: water transport model, SNOWPACK, preferential flow, runoff

1. INTRODUCTION

The arrival of liquid water at the snow base affects the stability of the snow and sometimes results in wet-snow, causing full-depth avalanches. Therefore, modeling the liquid water transport in snowpacks and estimating the liquid water arrival time at snow bases are important for predicting full-depth wet snow avalanches. Hirashima et al. (2010a) developed a one-dimensional water transport model and incorporated it into SNOWPACK (Lehning et al., 1999). After that, Hirashima et al. (2010b) compared simulated runoff amounts with observed runoff data by lysimeter. Although the model reproduced the water reduction curve, the calculated peak amount of runoff was delayed from the observation. Wever et al. (2014) implemented Richards' equation into the SNOWPACK model and reproduced the runoff amounts with pragmatic strategy. However, they mentioned that preferential flow has a more pronounced effect on the internal snowpack microstructure and on wet snow avalanche formation. The one-dimensional approach and the absence of preferential flow were found to have some drawbacks when used to predict wet snow avalanches (Mitterer et al., 2011).

Numerical snowpack model that considers the preferential flow effect was first developed by Katsushima et al. (2009); however, they did not consider the mechanism of preferential flow. Instead, they simply adjusted the simulated results to conform to the results of snow pit observation data after discharging extra liquid water, thereby accounting for the effect of preferential flow. Recently, a multi-dimensional water transport model was developed to simulate water infiltration by introducing a way to consider preferential flow. The present version of this model does not consider various snow processes such as snow settling, snowmelt, or the refreeze process, but rather, it considers heterogeneous water transport. Therefore, combining these various snow processes with the SNOWPACK model is necessary to apply the multi-dimensional water transport model to the natural snowpack. In this study, simulations were carried out that combined the SNOWPACK model and multi-dimensional water transport model. Furthermore, simulations were performed to calculate the arrival of liquid water at the snow base and the discharge amount, which were then compared with the lysimeter data.

2. SIMULATION METHOD

The SNOWPACK model (Lehning et al., 1999; Hirashima et al., 2010a) was used to obtain the snow structure. The SNOWPACK simulation was

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carried out for the study field of the Snow and Ice Research Center, NIED, in Niigata prefecture, Japan. In this field, meteorological input data such as air temperature, relative humidity, wind speed, wind direction, solar radiation, longwave radiation, precipitation, and snow depth were observed over one-minute intervals, amounting to one hour of data. Discharge amount was observed in multi-lysimeter (3 X 3 m area) consisting of nine small 1 X 1 m lysimeters. Figure 1 shows the simulated grain type, water content, and discharge amount by SNOWPACK in the winter of 2011/2012.

Using the results from the SNOWPACK simulation, the water transport simulation was carried out using the multi-dimensional model (Hirashima et al., 2014a). In the multi-dimensional water transport model (usually two- or three-dimensional), the simulated area, grid size, grain size, snow density, and initial water content for each grid were arbitrarily determined. The results of the SNOWPACK model simulation were used as the initial conditions. The height of the simulation area was set identical to the simulated snow depth by SNOWPACK and the width of the simulation area was set at 40 cm. The grid size was set at 2 cm. The SNOWPACK simulation outputs–such as snow depth, stratigraphy, layer thickness, grain size, and snow density just before the snowmelt–were used as initial data for the water transport model. In nature, grain size and snow density in the same layer are heterogeneous rather than homogeneous. Furthermore, this heterogeneity has significant effects on the formation and development of the preferential flow (Hirashima et al., 2014a). In this study, to consider the heterogeneity, normal random numbers were generated for each grid and used to vary the grain sizes. The standard deviation of the distribution frequencies was 20%, which is the same value used in Hirashima et al. (2014a).

The rate of water supply was determined from the amount of hourly rain and snowmelt estimated from the meteorological data and the SNOWPACK results. The rain amount was estimated to be the same value as the precipitation when the air temperature was above 1.5 °C. The amount of snow melt was estimated using the following energy balance equation:

$$M=10^3 \cdot (Q_h+Q_e+Q_{sn}+Q_{ln})/(L_f \cdot \rho_w) \qquad (1)$$

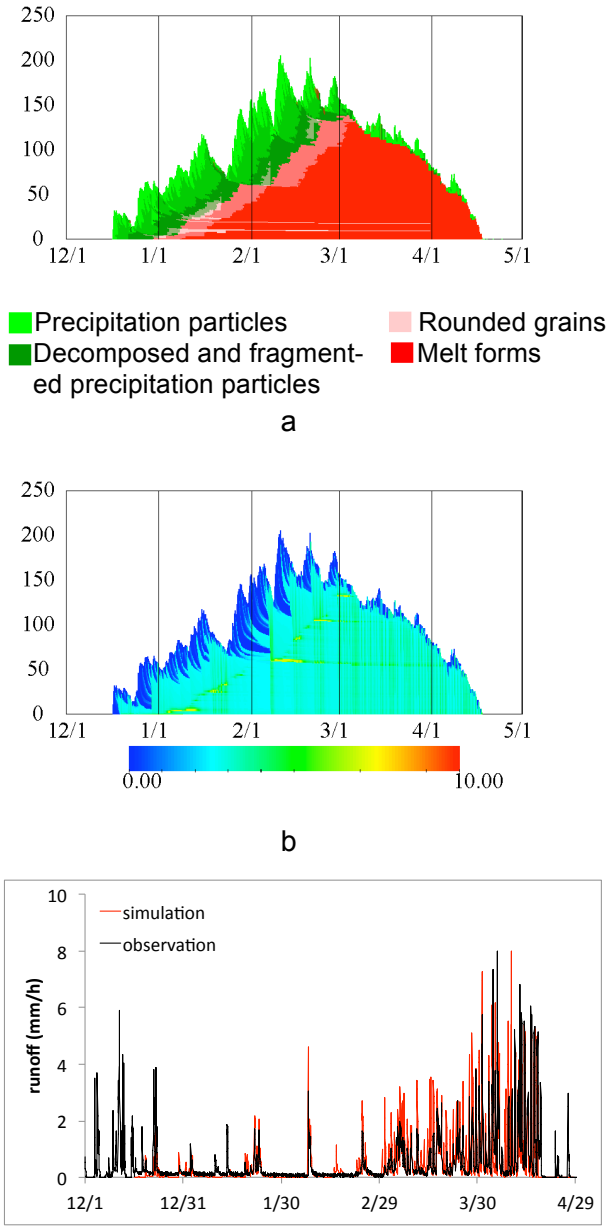


Fig. 1: Simulated snow profiles by the SNOWPACK model in winter of 2011/2012, Nagaoka (a) grain type (b) water content (c) discharge.

where M is the amount of snow melted within one second (mm/s), Q_h is the sensible heat flux (W/m^2), Q_e is the latent heat flux (W/m^2), Q_{sn} is the net shortwave radiation (W/m^2), Q_{ln} is the net longwave radiation (W/m^2), and L_f is the latent heat for fusion (kg/J). These fluxes were obtained from SNOWPACK's results. In the warm-snow

region of Nagaoka, events of rain on snow and snowmelt occurred frequently. In this study, nine events in which more than 30 mm of snowmelt or rain water supplied in one event were extracted in the winter of 2011/2012. The multi-dimensional water transport model simulation was performed for each event. Note, the present version of the water transport model considers only the water transport process and neglects the decrease in snow depth caused by snow densification and snowmelt. To estimate the effect of the multi-dimensional simulation, a simulation using one-dimensional water transport was also carried out for the same events.

3. RESULTS

The results of this study are for two rain on snow events that occurred on February 6–8 and March 23–25. Figure 2 displays the water content profiles simulated by SNOWPACK.

In the initial condition of the February 6–8 case, about half of the upper snow layers were dry and most of the lower snow layers were wet before the rain commenced. During this period, the rainfall was 37.5 mm and the snowmelt amount was an estimated 7 mm. In the initial condition of the case of March 23–25, all snow was already wet. In this period, the rainfall was 18.5 mm and the snowmelt amount was an estimated 15 mm.

Figures 3 and 4 show the simulated temporal change of water content distributions for the events on February 6–8 and March 23–25, respectively. Water content was shown using same color with the SNOWPACK results (blue is dry, light blue is wet, green and yellow signify large water content, and red is water ponding).

In the case of February 6–8, during liquid water infiltrated into the dry snow, preferential flow formed in the multi-dimensional simulation (see Fig. 3k). Comparing the results of the one-dimensional simulation with the multi-dimensional simulation revealed that the two have different water content distribution, especially in the initially dry snow (compare Figs. 3d-g and k-n). Figure 4, or the depiction of all wet snow simulated in the multi-dimensional simulation, showed heterogeneous water content distribution; however, patterns of vertical water content distribution were similar to the one dimensional simulation.

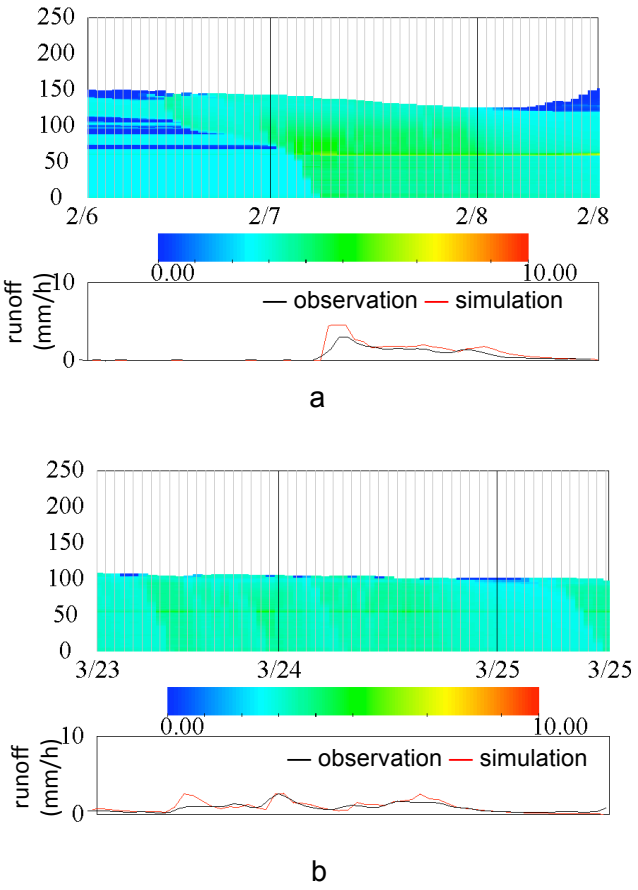


Fig. 2: Simulated volumetric water contents (%) by the SNOWPACK model. Lower figure is runoff amount. a: February 6–8, b: March 23–25.

Figure 5 shows the temporal changes of runoff amounts obtained from these simulations, with the measurement results observed by lysimeter. For reference, simulated runoff amounts found within SNOWPACK and the amount of water supply were also shown. In the case of February 6–8, the simulated runoff determined within the multi-dimensional simulation was off by nearly one hour from the results of the one-dimensional simulation (compare green and blue). Formation of the preferential flow accelerated vertical water movement in the multi-dimensional model. However, even in the multi-dimensional model, the results were delayed by about 3 hours from the observations. Simulation runoff amounts in the case of March 23–25 were also delayed. Furthermore, SNOWPACK results obtained better reproducibility with smaller delay; however, the results did not take the formation of preferential flow into account. The

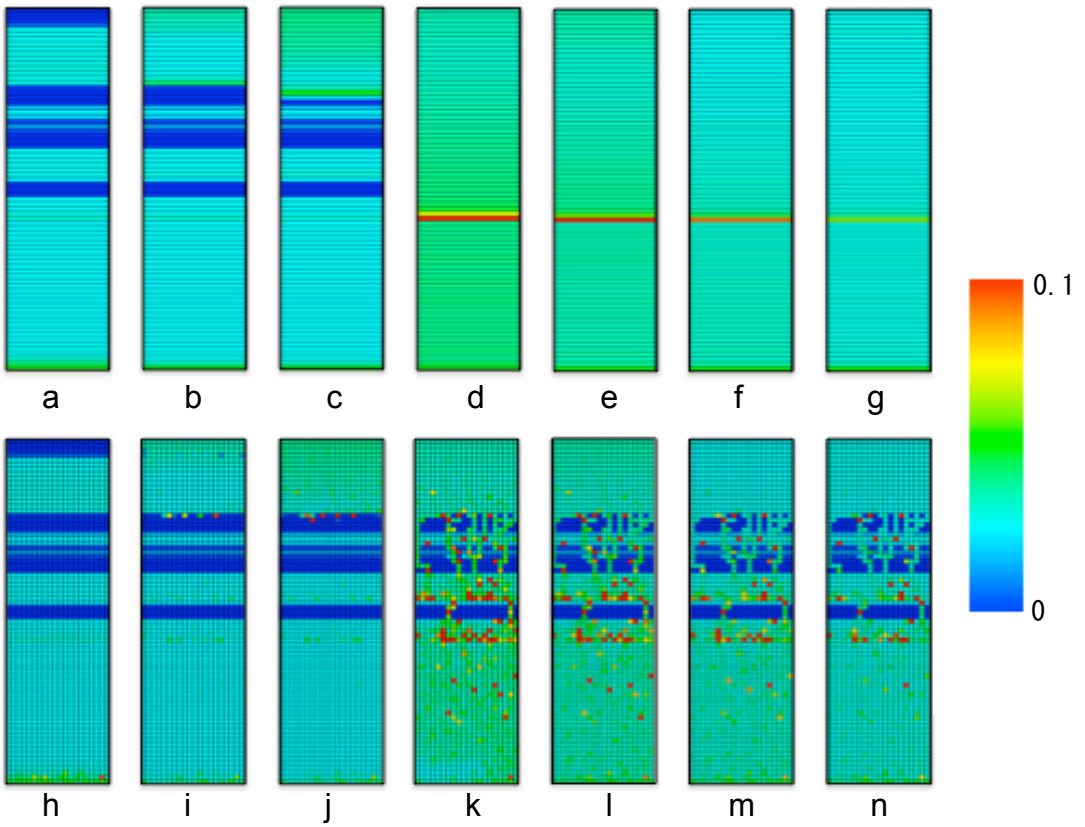


Fig. 3 Simulated water content distribution in the period of rain on snow event February 6–8 (a–g: one-dimensional simulation, h–n: multi-dimensional simulation). Water content distributions were shown with intervals of 10 hours.

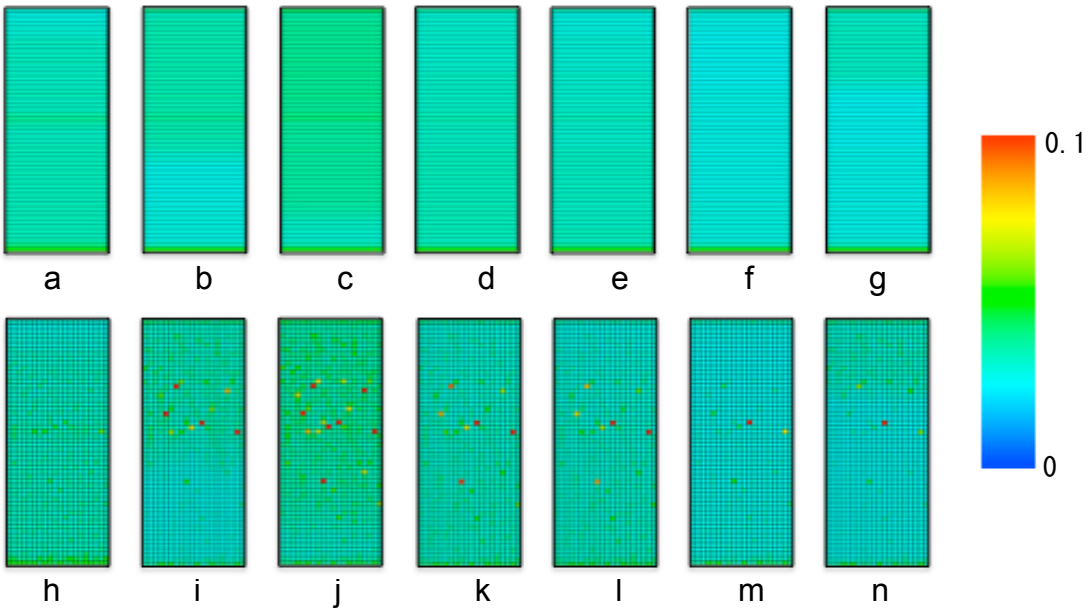
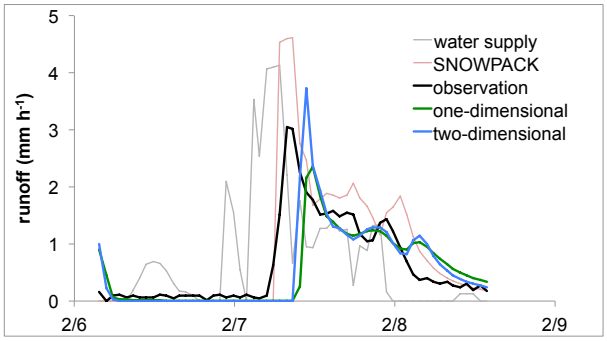
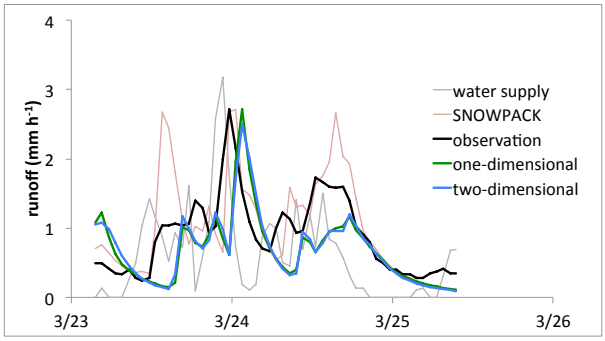


Fig. 4 Simulated water content distribution in the period of rain on snow event March 23–25 (a–g: one-dimensional simulation, h–n: multi-dimensional simulation). Water content distributions were shown with intervals of 10 hours.



a



b

Fig. 5: Temporal change of runoff amount estimated by lysimeter and model simulations. Amount of water supply and SNOWPACK simulation results were also shown as references (a) February 6–8 (b) March 23–25.

result suggested the necessity of the following improvements in order to reproduce the timing of the runoff accurately. While liquid water infiltrates into the new snow, snow grows in density rapidly and sometimes forms snow dimples. The formation of snow dimples leads to the concentration of liquid water at the concave interface between the snow layers and the development of preferential flow. That being said, the present version of the water transport model does not consider the densification, which signifies one of the shortcomings of this model. Modeling of this densification of new snow with the interaction of liquid water is not explored in this manuscript. Consideration of the transformation of simulation grids using some computational technique (e.g. finite element method) will allow for implementation of the densification into the multi-dimensional water transport model.

Another initiative to better moderate the delay of runoff is to take the snow density into account in the equation of water entry suction. In the equation, although the dependence of grain size was accounted for, snow density was not considered (Katsushima et al., 2013). On the other hand, the equation estimating the suction for the wet snow is the function of grain size and snow density (Yamaguchi et al., 2012). In both of their experiments, dense snow with a dry snow density larger than 400 kg/m^3 was used. For this reason, water entry suction of snow with low density was not estimated accurately, and the formation of preferential flow was not reproduced correctly. Further experiments to measure the entry suction of water in order to better define the dependence of snow density will help to accurately simulate the water infiltration and runoff.

4. SUMMARY AND FUTURE WORKS

The combination simulation of SNOWPACK and the multi-dimensional water transport model was tested. The results from the simulation revealed that the consideration of heterogeneous water transport, and preferential flow using the multi-dimensional model led to earlier liquid water arrival at the snow base. However, moderating the delay of the simulated runoff amount by considering the heterogeneous water transport was insufficient. Parameters used in the multi-dimensional water transport model were based on experimental results using dense snow for which the dry snow densities are larger than 400 kg/m^3. As such, the weakness of the current version of this model considers the liquid water infiltration as low density snow. Modeling the relationship between water entry suction and snow density, considering the densification of low-density snow, and reproducing snow dimples are all left for future research, for which the temporal change of runoff amount must be estimated accurately.

There are two ways one can apply the multi-dimensional water transport model with the natural snowpack. Firstly, one can use the output data simulated by the numerical snowpack model as the input data of this model (this study). Secondly, one can fabricate parameters for the effect of heterogeneous water transport in order to implement the numerical snowpack model. Our other study (also belonging to this workshop) contains a sensitivity experiment focusing on the effect of a capillary barrier and preferential flow (Hirashima et al. 2014b) toward the latter application. Both studies are in progress, and the goal of these studies is to

develop the numerical snowpack model, which accounts for the influence of preferential flow.

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