ESTIMATION OF WATER INFILTRATION THROUGH CHANNELS IN SNOWPACK ON A SLOPE

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ABSTRACT: Water infiltration into snowpack has considerable effect on snowpack properties such as layer structure, grain type, density, and water content, which are important factors in wet avalanche formation. Water infiltration into snowpack is non-uniform and preferentially flows in vertical water channels. To obtain better representation of snowpack in simulations of wet snow, previous work has proposed a multilayer snow model that includes parameterization of the vertical water channel process based on observations collected on flat land. However, based on winter observations of pit snow obtained in earlier work, we suggest that differences in the amount of water infiltration through channels within snowpack on a slope and on flat land, can generate notable differences in the ratio of the total thickness of the layers composed of melt forms to the thickness of all layers (MF_r).To develop a method to estimate the amount of water infiltration into water channels on a slope, for better representation of snowpack simulation, we conducted observations for an additional two winters and analyzed the results from the three winter periods. Our analysis shows that the use of the simple method, which entails tuning a threshold value of liquid water saturation at the wetting front to adjust the amount of water flowing into the water channels, can represent MF_r with an approximate root mean square error of 10%.

KEYWORDS: Water infiltration of snowpack; Wet snow; Snow stratigraphy; Snowpack model

1. INTRODUCTION

Infiltration of liquid water into snowpack plays an important role in the formation of wet avalanches through the alteration of snow layer structure, grain type, density, water content, and strength (Kattelmann, 1985; Conway et al., 1988; McClung and Schaerer, 2006; Baggi and Schweizer, 2009).

Water infiltration into snowpack is non-uniform and preferentially flows in vertical water channels. After the water channels had formed, water was drained from the wetting front, which caused a decrease in the amount of water flowing down into the snowpack, except at the vertical water channels, which occupied only a very limited part of snowpack. The decrease in the amount of water flowing down into the main part of the snowpack prevented wet-snow metamorphism. Thus, to simulate wet snow aiming to wet avalanche forecasting, grasp on amount of water flowing down into vertical water channels is very important.

To obtain better representation of snowpack in simulations of wet snow, previous work has proposed a multilayer snow model that includes parameterization of the vertical water channel process based on observations collected on flat land（Katsushima et al., 2009). However, based on winter observations of pit snow obtained in earlier work, we suggest that differences in the amount of water infiltration through channels within snowpack on a slope and on flat land, can generate notable differences in the ratio of the total thickness of the layers composed of melt forms to the thickness of all layers（Ikeda et al., 2013).

To develop a method to estimate the amount of water infiltration into water channels on a slope, for better representation of snowpack simulation, we conducted observations for an additional two winters and analyzed the results from the three winter periods.

2. STUDY SITE AND METHODS

2.1 STUDY SITE

The study was conducted at the Tohkamachi Experimental Station of the Forestry and Forest Products Research Institute in Niigata, Japan (37° 08' N, 138° 46’ E; 200 m a.s.l.). The average max-

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imum annual snow depth at the site is 2 m, and the average temperature is near 0°C, even during January and February. Snowmelt and rainfall often occur even during mid-winter and typically create moist or wet snowpack throughout the winter. Study site is selected to avoid typical wind loading and wind erosion (Figure 1). The slope angle of was 40° and slope aspect was NE.

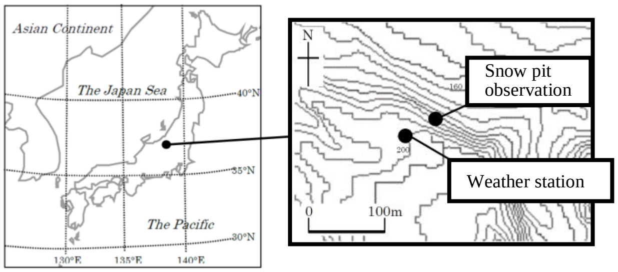

Fig. 1 Study site

2.2 OBSERVATION METHODS

2.2.1 Meteorological observations

The following meteorological data were collected automatically every hour at a weather station located at flatland (Figure 1): precipitation (including both liquid and solid types), snow depth, air temperature, humidity, wind speed, shortwave radiation (upward and downward), net radiation, and heat flux to the soil at ground level. The form of precipitation (rain or snow) was predicted using the method proposed by Yamazaki (1998), which uses the estimated value of the wet-bulb temperature of 1.1°C as the threshold value.

2.2.2 Snowpack observations

In each snowpack, a snow pit was dug from the snow surface to ground level. Observations were conducted approximately every 20 days on selected dates from January to April 2012 (5 and 25 Jan., 15 Feb., 5 and 26 Mar., and 13 Apr.), from December 2012 to April 2013 (15 Dec., 7 Jan., 15 Feb., 5 and 26 Mar., and 16 Apr.) AND from January to April 2014 (6 and 24 Jan., 14 Feb., 5 and 25 Mar.). In total, 17 pits were dug and observed. To obtain better representativeness for each site (eliminate spatial variability as much as possible), we dug forward approximately 1 m from the pit wall that was last observed to make a snow pit wall with a width of 1.5 m for each measurement and confirmed by the digging that there was no notable spatial variability. We also conducted such an evaluation at three completed walls (one 1.5-m and two 1-m width walls). The items observed and methods used are as follows.

- Snowpack layer structure: the position and thickness of layers were determined by visual means and by touch using the hands or fingers.
- Snow grain type and diameter: determined by using a snow crystal screen, which had three grids of 1, 2, and 3 mm, and a hand loupe (10×).
- Hardness: measured by push gauge (Takeuchi et al., 1998) every 10 cm (or greater as needed to measure all layers).
- Snow temperature: measured with a thermistor thermometer every 10 cm.
- Density: measured with a 100-cm3 sampler every 10 cm (or greater as needed to measure all layers).
- Water equivalent of total snowpack: measured with a snow sampling tube (38-cm2 cross section) with enough length to sample all snow layers at once from the surface to ground.

2.3 ESTIMATION OF WATER INFILTRATION THROUGH CHANNELS

we estimated the suitable amount of water flowing into vertical water channels to represent the at each site by using a one-dimensional snowpack model developed by Katsushima et al. (2009) that included a parameterization of the vertical water-channel process in snowpack. In this model, the snowpack is separated virtually into a uniform part and a water channel part. When the simulated liquid water saturation at the wetting front $S_{rk}(t)$ exceeds the threshold value S_t, the amount of water flowing into the water channel part $A_{wc}(t)$ (kg m$^{-2)}$ is estimated as follows and then removed from the water flowing into the uniform part (the removed water is drained from the wetting front to the ground interface):

$$A_{wc}(t) = (S_{rk}(t) - S_t) \times \left(1 - \theta_{vol.i.k}(t)\right) \times \rho_w \times h_k(t) \;, \qquad (1)$$

where $\theta_{vol.i.k}(t)$ is the volumetric ice content ratio in the simulated wetting front, ρ_w is the wet snow density (kg m^{-3}), and $h_k(t)$ is the layer thickness (m) at the simulated wetting front layer k. S_t is tuned to obtain better representation of the simulated value of Melt Form (MF) ratio MF_r (%) (the ratio of the total thickness of the layers constituting the MF to the thickness of all the layers of the snowpack) for the uniform part by using the root mean square error (RMSE) between simulated and observed values as an indicator. MF_r was calculated as follows:

$$MF_r = \frac{\sum_{i=1}^{n} h_{MF_i}}{HS} \times 100 \,, \qquad (2)$$

where h_{MF} is the height of each layer constituting the MF, n is the number of layers constituting the MF, and HS is the total snow height of the snowpack.

The equation for saturated permeability was changed to that proposed by Calonne et al. (2012), and the equation for the water retention curve was changed to that proposed by Yamaguchi et al. (2012) to obtain a better representation of the impermeable process associated with layers consisting of fine snow grains over layers consisting of coarse snow grains.

For the calculations, meteorological data (air temperature, humidity, precipitation, wind speed, atmospheric pressure, and heat flux to the soil at the ground) observed at the weather station were used. Net shortwave radiation and net longwave radiation were estimated as follows.

Shortwave radiation (downward) was estimated as the sum of the three values described below. Direct-beam shortwave radiation and sky-diffuse shortwave radiation at weather station were computed based on the shortwave radiation (downward) measured at the weather station using the method proposed by Reindl et al. (1990).

-Direct-beam shortwave radiation was estimated from the value at weather station by considering the angle between the solar beam and a line perpendicular to the slope (interception by surrounding terrain was neglected).

-Sky-diffuse shortwave radiation was estimated from the value at weather station using the method proposed by Perez et al. (1990).

-Diffuse shortwave radiation on the slope from the surrounding terrain at SLP was estimated from the relationship of slope aspect and slope angle using a geometrical method.

The shortwave radiation (upward) was estimated from the estimated shortwave radiation (downward) on the assumption that the albedo had the same value as at weather station. Net longwave radiation was estimated from the estimated incoming and outgoing longwave radiation values at weather station using the method proposed by DeWalle and Rango (2008). Incoming and outgoing longwave radiation values at weather station were estimated as follows.

-Incoming longwave radiation at weather station was estimated by subtracting outgoing longwave radiation, which was estimated from the net longwave radiation at weather station by the method mentioned below.

-Outgoing longwave radiation at weather station was estimated assuming that the snow surface temperature was 0°C and that snowpack emissivity was 0.97 (Kondo, 1986).

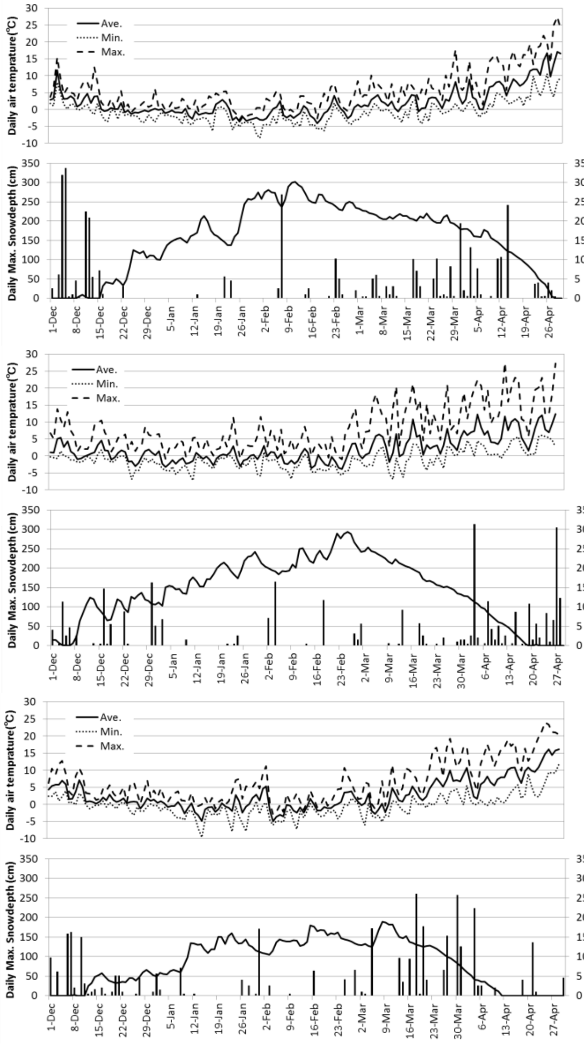

Fig. 2 Observed weather data for each winter (upper:2011-12, middle:2012-13, bottom:2013-14)

3. RESULTS

The meteorological conditions of the study site from December to the end of April for each winter were shown in figure 2. The maximum snow depth and total amount of rainfall for each period were 2011-12: 302 cm and 376.4 mm, 2012-13: 293 cm and 312.6 mm, 2013-14: 189 cm and 354 mm respectively. Rainfall events occurred often even during January and February (total rainfall for January and February were 2011-12: 63.1 mm, 2012-13: 57.8 mm, 2013-14: 59.6 mm). The average air temperature during the period were 2011-12: 5.6 °C, 2012-13: 6.0 °C, 2013-14: 6.7 °C and it was common for the daily maximum air temperature to exceed 0 °C even during January and February.

Results of analysis were shown in table 1, table 2and figure 3. Two types of S_t were estimated. S_t-1 was estimated by using data of each winter and S_t-2 was estimated by using data of 3 winters. Further, amounts of water flowing into vertical water channel were estimated for both of St-1 and St-2.

S_t-1 for each winter were estimated to be 7.41% for 2011-12, 7.22% for 2012-13 and 7.20% for 2013-14, and S_t -2 was estimated to be 7.31%. Root mean square error (RMSE) between observed MF_r and estimated MF_r by using S_t 1 for each winter were 1.9 % for 2011-12, 12.6 % for 2012-13 and 6.4 % for 2013-14. On the other hand, it was 4.2 % for 2011-12, 13.6 % for 2012-13 and 8.9 % for 2013-14, when using S_t -2. The comparisons between observed and simulated transitions of snow pack layer structure for each winter were shown figure 4. Both simulation results well represent characteristic of transitions of snow pack layer structure such as state that Rounded Grains layers remained at middle part of snowpack and the timing when all layers turn into Melt Form layers, and representation of MF_r does not have the large difference even if using whichever of S_t-1 and S_t-2.

However, such small difference of S_t can bring the large difference on amount of water flowing into vertical water channel (figure 5). Cumulated amount of water flowing into vertical water channel for each winter was estimated to be 27 mm (S_t-1) and 88 mm (S_t-2) for 2011-12, 246 mm (S_t-1) and 93 mm (S_t-2) for 2012-13 and 210 mm (S_t-1) and 42 (S_t-2) for 2013-14.

Table 1. Results of analysis for each period

Observed Period	S_t-1 (%)	RMSE for MF_r (%)	CA_{wc} (mm)	AWC_r (%)
2011-12	7.41	1.9	27.4	1.9
2012-13	7.22	12.6	246.1	17.2
2013-14	7.20	6.4	210.1	18.6

$\mathrm{CA_{wc}}$: Cumulated amount of vertical water channel flow, $\mathrm{AWC_r}$: The ratio of the accumulated amount of water infiltrating the vertical water channel to the total accumulated infiltrated water

Table 2. Estimations of RMSE for $\mathrm{MF_r}$, $\mathrm{CA_{wc}}$, $\mathrm{AWC_r}$ for each period by using S_t-2 (7.31%)

Observed Period	RMSE for MF_r (%)	CA_{wc} (mm)	AWC_r (%)
2011-12	4.2	88.4	6.0
2012-13	13.6	92.7	6.5
2013-14	8.9	41.9	3.7

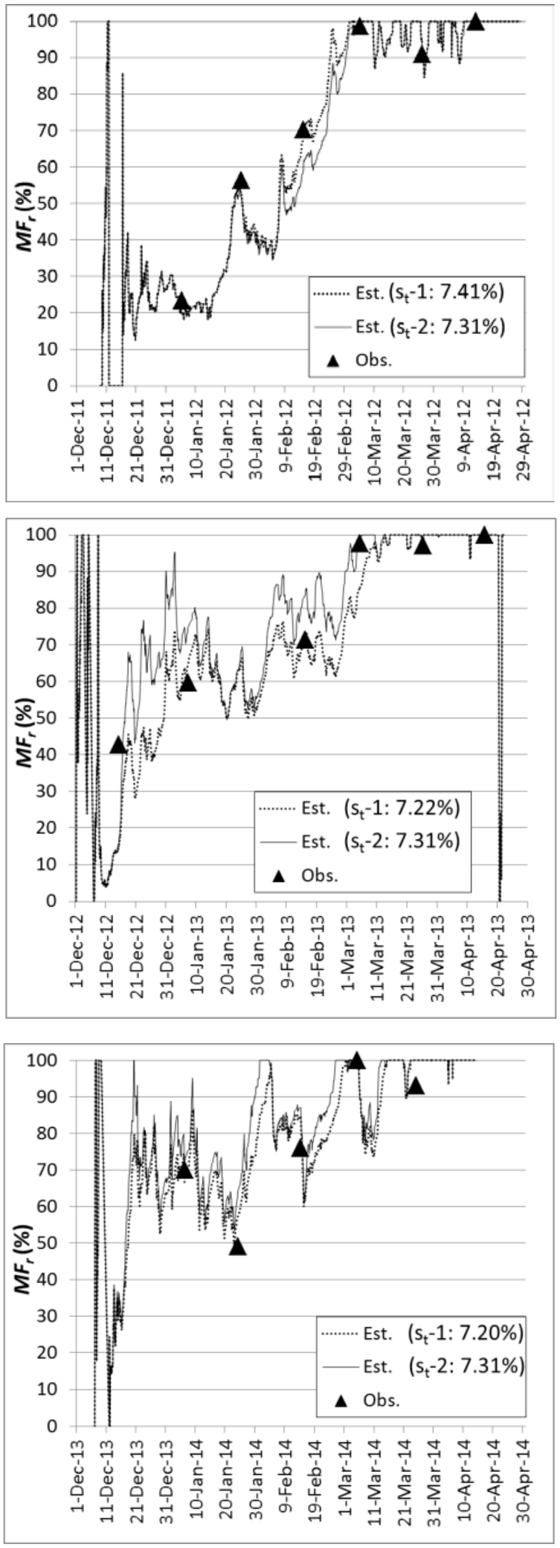

Fig. 3 Comparisons between observed and simulated MF_r (upper:2011-12, middle:2012-13, bottom:2013-14)

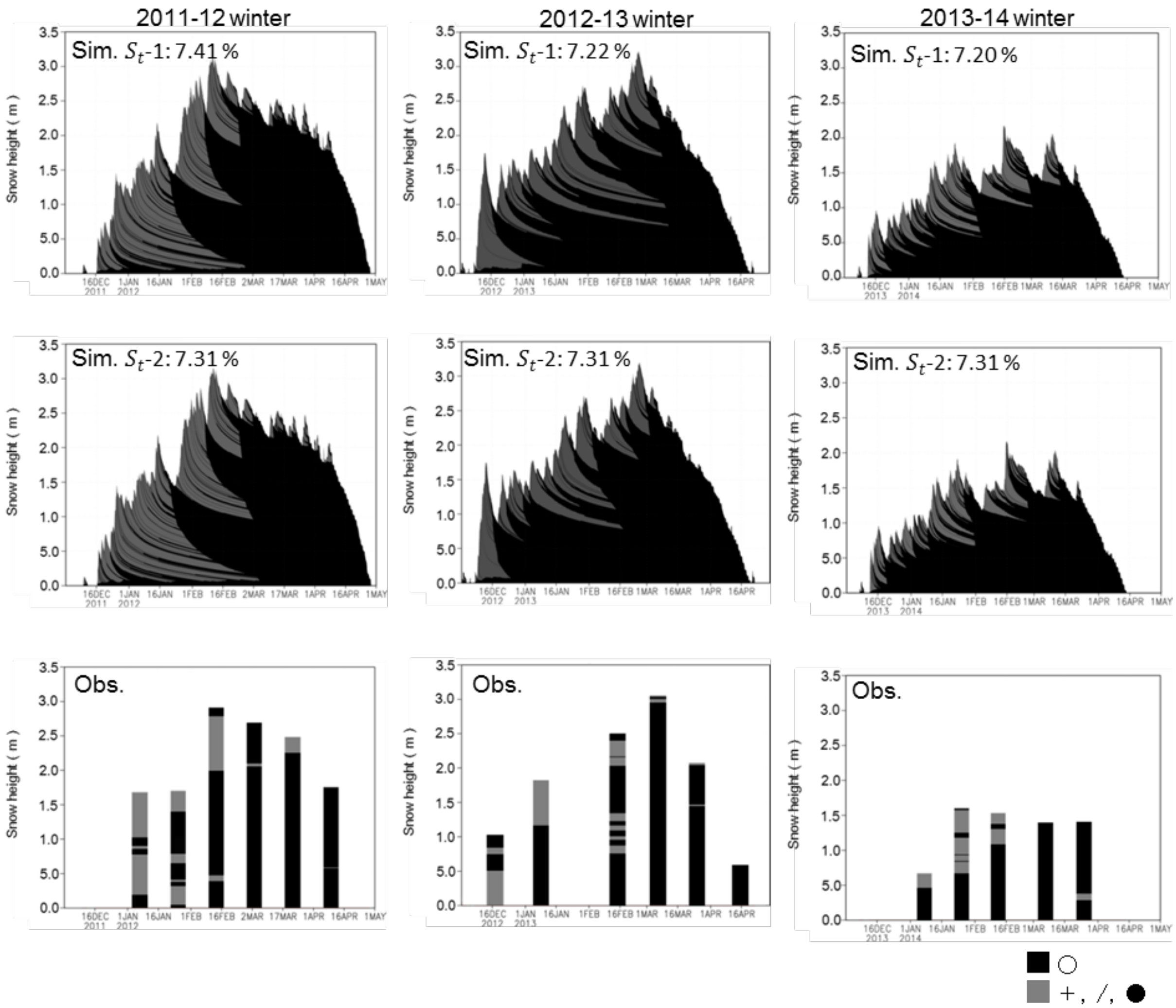

Fig. 4 Comparisons between observed and simulated transitions of snow pack layer structure for each winter (left: 2011-12, middle: 2012-13, right: 2013-14)

4. DISCUSSION AND CONCLUSION

To develop a method to estimate the amount of water infiltration into water channels on a slope, for better representation of snowpack simulation, we analyzed the results from the three winter periods observations by focusing on the representation of MF_r (the ratio of the total thickness of the layers constituting the MF to the thickness of all the layers of the snowpack).

Our analysis shows that the use of the simple method , which entails tuning a threshold value of liquid water saturation at the wetting front to adjust the amount of water flowing into the water channels (S_t,) can represent MF_r with an approximate root mean square error of 10%. However, even quite small difference of S_t that did not bring serious difference on the representation of MF_r and snow layer structures brings large difference on simulated amount of water flowing into the water channels. Because water flowing into the water channels will reach the bottom of snowpack and it will make weak bottom snow layer or slippery ground surface, these are very serious difference to use full depth wet avalanche forecasting. To eliminate the difference mentioned above and propose a general method for estimating the amount of water flowing into water channels at slope with a one-dimensional snowpack model that would be useful for operational avalanche forecasting, we believe that it is valuable to investigate the relationship between the occurrence of preferential flow and the balance of water-entry capillary pressure and the supplied water flux at the wetting front and implement it into a water movement model.

Further the timing that the water flowing into the water channels reaches the bottom is very important information for full depth wet avalanche forecasting, and it may be reaches faster than uniform flowing water. We believe that dynamic observations of water infiltration are necessary to get better representation of the timing on simulation.

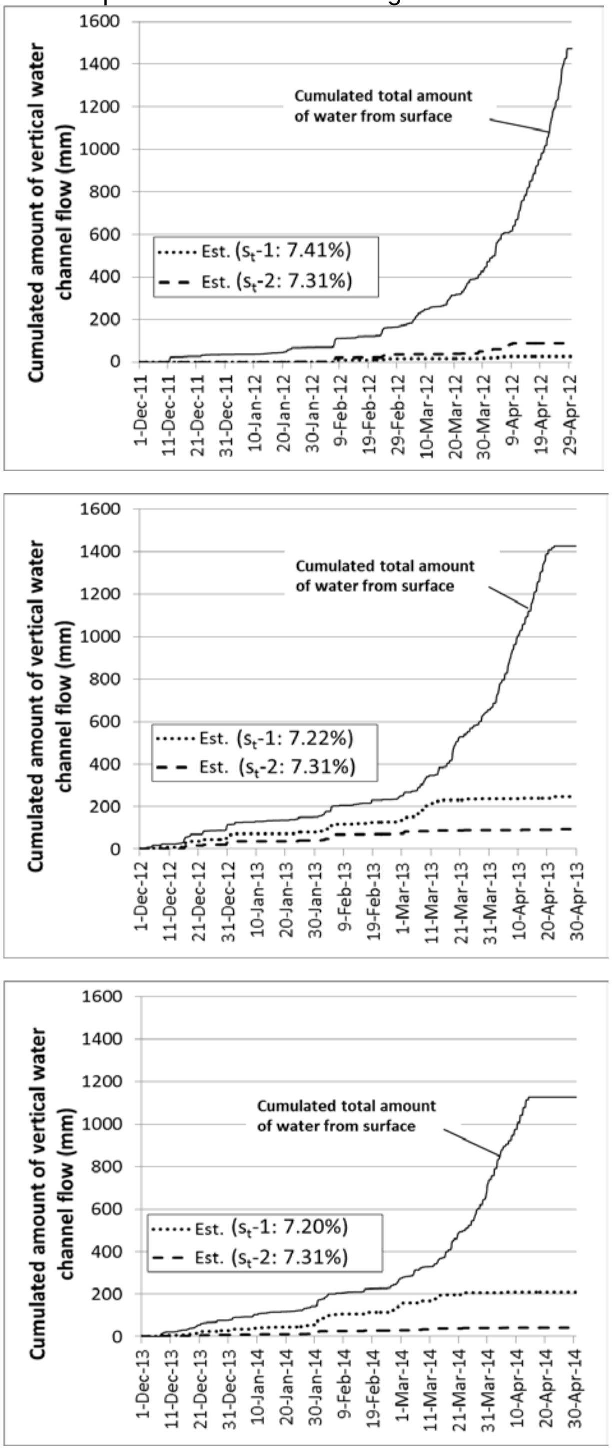

Fig. 5 Simulated amount of water flowing into vertical water channel (upper:2011-12, middle:2012-13, bottom:2013-14)

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