THE METHOD FOR ESTIMATING OUTFLOW FROM THE SNOWPACK USING THE SIMPLIFIED HEATBALANCE MODEL AND THE PERCOLATION MODEL

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ABSTRACT: To ensure the safety of train operations, it is important to estimate the outflow from the bottom of snowpack which might incur a full-depth avalanche. Therefore, the authors examined a simplified method for estimating the outflow from the bottom of snowpack, which can be applied to railway disaster prevention, on the basis of heat balance observations, snowmelt observations and previous studies. Consequently, the simplified method, which combines a snowmelt (heat balance) model and a percolation model, yields a good estimate of the outflow from the bottom of snowpack at 1hour intervals using four input data available from the nearest AMeDAS: i.e., air temperature, precipitation, wind speed and duration of sunshine.

KEYWORDS: snowmelt, outflow from snowpack, heat balance method, full-depth avalanche

1. INTRODUCTION

In snow-covered areas, at the beginning of spring, a large amount of snow melts on the snow surface and the water infiltrates the accumulated snow. In recent years, even in winter, temporary temperature rises have been observed and large volumes of rain and snowmelt have been recorded (Kawashima et al.,2002). For example, in Sapporo on January 23, 2009, the temperature rose to 7.6 ℃ in winter, and 18.5 mm of precipitation was observed. In such situations, it is known from a qualitative point of view, that water between snow and soil reduces the bearing capacity of the snowpack intensity of the snow, creating the danger of a full-depth avalanche increase. However, it is still unknown the extent to which rain or snowmelt affects the danger of a full-depth avalanche. Therefore, in railway companies, when the increase of the temperature or rain was observed in winter, rounds and watches are carried out based on empirical rules. In recent years, the number of employees with abundant experience however, is decreasing. In order to carry out suitable rounds and watches , it is important to clarify the relationship between snow-melt and full depth avalanche occurrence, which should then be taken into account in setting guidelines for rounds and watches in winter.

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2. ESTIMATION OF THE OUTFLOW FROM THE BOTTOM OF THE SNOWPACK

To estimate the outflow from the bottom of the snow pack, a method can be used to estimate the outflow directly (water equivalent method, lysimeter method") or indirectly (degree-day method)(The Japanese Society of Snow and Ice Hokkaido-branch,1991)(Kondo,2000). The water equivalent method calculates outflow from the weight of the snowpack using snow pillows. The lysimeter method observes percolation through the snow pack and is set on the ground surface. Both methods have the advantage of offering direct observation of the outflow, but they also need large spaces (10 m^2) to set the observation equipment and careful maintenance management to continue exact measurement. Therefore, it is not reasonable to install this observation equipment along tracks from the view point of cost and maintenance. On the other hand, the degree-day method calculates the outflow in relation to temperature simply using empirical rules based on the relationship between outflow and temperature. Because this method is easy, and is the same time cost efficient compared with other methods, it was further investigated with a view to application as a trackside disaster prevention measure. For example, we use this method to predict avalanche along railroad, and when the avalanche is predicted we will make official announcement to the station etc. The precision of the degree-day method is a daily moving average. As such it was difficult to compute outflow to reach a 1 hour time resolution required for railroad disaster prevention. The present research aimed to satisfy this requirement by examining techniques to estimate outflow per hour. In order for this method to be applied to railway disaster prevention it is preferable that input data be easily obtained. It was therefore determined that input values for this estimation method should be the observed data collected from the nearest AMeDAS (Automated Meteorological Data Acquisition System). Figure.1 shows the process for estimating outflow from the snowpack. It is necessary to estimate the outflow accurately every hour. Two phenomena found in snowpack, i.e. “snowmelt at snow-surface” and “infiltration in snowpack” where therefore considered separately. A model was then designed to estimate each phenomenon, based on weather/snowmelt observations and past research results. The following sections describe how each model was created and present the estimations subsequently obtained.

3. OBSERVATION

Snowmelt and weather data from the Shiozawa Snow Testing Station (Minami-Uonuma, Niigata,Japan) during the winter of 2011 were observed to obtain the data needed to develop a method for estimating outflow from the bottom of the snowpack. Observations were made of temperature, humidity, precipitation, snow depth, wind direction, wind speed, air pressure and solar radiation (hours of sunshine) (see Section 4.1). Outflow was measured with a lysimeter. Measurements were collected every ten minutes for 110 days from January 6 to April 25 (date when no snow was left) in 2012. Below is a sample of snowmelt observation data.

4. BUILDING A MODEL FOR ESTIMATING THE SNOWMELT AT THE SNOW SURFACE

Snowmelt ($M_{S:}$ amount of snowmelt at the snow surface) was calculated using the heat-balance

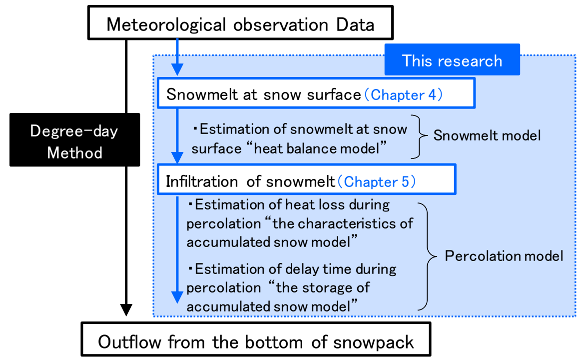

Fig. 1: Procedure for estimating outflow from under the snowpack

method that has been widely used in snowmelt estimation analysis (Fig. 1). This study first presents an outline of the heat-balance method, followed by the description of a method for calculating M_s from the results of observations (four types of meteorological data: temperature, precipitation, wind speed, hours of sunshine).

4.1 *Estimation of the snowmelt using the heat balance method*

The heat balance method is a method for calculating the amount of heat in snowmelt estimation (Q_M) from the heat balance at the melting snow surface (Fig. 2). Q_M at each time can be found from a heat budget (Equation 1).

$$Q_M = Q_R + Q_H + Q_L + Q_P + Q_C \qquad (1)$$

where Q_R is net radiation, Q_H is detectable heat exchange, Q_L is latent heat exchange, Q_P is heat content of liquid precipitation, Q_C is heat exchange at snow surface. In equation 1, the snow surface was defined as the reference plane, the amount of heat into the reference plane is assumed to be positive, and the amount of heat out of the reference plane negative, and *the* unit of heat is represented as W/m^2. Ms is calculated by dividing Q_M (W/m^2) obtained in equation 1 by latent heat of ice (=0.334×106J/kg). The methods for calculating each heat quantity shown in equation 1 are shown.

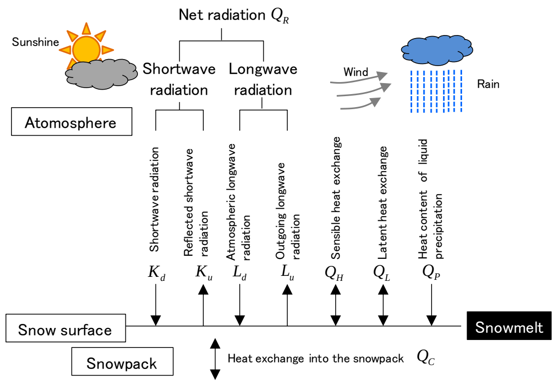

Fig. 2: Heat balance method (pictorial representation)

(1)Net radiation Q_R

Net radiation Q_R can be found from equation 2 including the net shortwave radiation K_d, the reflective shortwave radiation K_u, the net longwave radiation L_d, the outgoing longwave radiation L_u (Kondo,2000)(Maeno and Fukuda,1994)(Hay and Fitzharris,1988).

$$Q_R = K_d + K_u + L_d + L_u \tag{2}$$

(2) Detectable heat exchange Q_H, latent heat exchange Q_L

Detectable heat exchange Q_H and latent heat exchange Q_L can be found from equation 3 and equation 4 by bulk method assuming neutral atmospheric conditions.

$$Q_H = C_H \rho C_p (T_a - T_s) u_z \tag{3}$$

$$Q_L = C_E \rho l (0.622/AP)(e_z - e_0) u_z \tag{4}$$

where C_H and C_E is the bulk index for detectable heat flux and latent heat flux (1.74×10^{-3}), ρ is density of air (kg/m^3), C_p is the specific heat at constant pressure (1005 J/kg/K), Ta is temperature (℃), u_z is wind speed at z(m) above the snow surface (m/s), l is latent heat of vaporization (2.5×10^6 J/kg), AP (hPa) is air pressure at the observation site, ez (hPa) is water vapor pressure at z (m) above the snow surface, e_0 (hPa) is saturated water vapor pressure at the temperature of the surface snow.

(3) Heat content of liquid precipitation Q_P

Heat content of liquid precipitation Q_P can be found from equation 5.

$$Q_P = \rho_w C_w T_w P_r \tag{5}$$

where ρ_w is the density of water (1000 kg/m^3), C_w is the specific heat of water (4.186 J/kg/K), T_w is wet-bulb temperature (℃), P_r(kg) is precipitation.

(4) Heat exchange at the snow surface Q_C

Heat exchange at the snow surface Q_C is generated by the temperature gradient in the snowpack. If the snow is 0 ℃, Q_C is almost 0 (Maeno and Fukuda,1994). And if there is a temperature gradient in the snow, Q_C is smaller than the other elements. For this reason, in this study, we gave Q_C as 0 W/m^2.

4.2 <u>Estimation of the snowmelt using four types of meteorological data</u>

As shown in Section 4.1, if only weather observation data have been obtained, the heat balance method could be used to calculate snowmelt at the snow surface per hour regardless of the region. However there remains a problem in that many sorts of input data are necessary for apply the conventional heat balance method to railway disaster prevention. Therefore, in this section, a method was examined to see how to incorporate the weather/outflow observation data and the result of previous studies into the estimation process of each element required for the heat balance method, and to estimate the Ms from only four weather observation data. In the following, the method for estimating each element is described.

(1)Net Radiation Q_R

The net shortwave radiation K_d (that is given by the solar radiation onto the snow surface) was calculated from the solar radiation in the upper atmosphere (Kun and Toshio,2005). The amount to be reflected at the snow surface K_u (the reflective shortwave radiation) of K_d reaching the snow surface could be represented by the product of reflectance (albedo) α and K_d. Here, it is known that α is variable according to the amounts of moisture and

Tbl. 1: Temperature of snow surface T_s

Meteorological Condition	T_s
(a)$T_a \geqq 0$	$T_s = 0$℃
(b)Night time(Solar Radiation at the top of atmosphere =0), and T_a is decreasing (Radiative Cooling arising)	$T_s = T_a - 3$℃
Except the above (a) and (b)	$T_s = T_a$℃

Tbl. 2: Relative Humidity *rh*

Meteorological Condition	rh
$Pr > 0$	$rh = 90\%$
$Pr = 0$ and $T_a < 0$	$rh = 76\%$
$Pr = 0$ and $T_a \geqq 0$	$rh = 69\%$

Tbl. 3: Estimating Method of Snowmelt

Quantity of Heat	A meteorological element required for estimation
Net radiation $\boldsymbol{Q_R}$	T_a, P, S
Sensible heat exchange $\boldsymbol{Q_L}$	T_a, P, u_a
Latent heat exchange $\boldsymbol{Q_H}$	T_a, P, u_a
Heat content of precipitation $\boldsymbol{Q_P}$	T_a, P
Heat exchange into snowpack $\boldsymbol{Q_C}$	0W/m^2

dirt of the snow surface (Yamazaki et al.,1994), and α was calculated by the temperature at the time of snowfall causing, and the lapsed time after the snowfall, both of which are considered as an index. On the other hand, quantity of heat (the net longwave radiation) L_d given to a snow surface from the clouds and water vapor of the air was presumed from Ta and the sunshine duration S. Quantity of heat ejected from the snow surface towards the atmosphere (the outgoing longwave radiation) L_u is estimated from the temperature of the snow surface Ts (Maeno and Fukuda,1994). In addition, Ts was taken from the value of Tbl. 1 which was the result of the weather/outflow observation.

(2) Detectable heat exchange Q_H, Latent heat exchange Q_L

The density of the air (ρ) used in equatin 3 and equation 4 was presumed from temperature Ta, relative humidity rh and local atmospheric pressure AP (Kondo,1994)(Meteorological Society of Japan,1996)(Japan Meteorological Agency,2002). Since it is difficult to estimate rh from four observation data and the influence which it has on transfer heat is small, values for this parameter were taken from Tbl. 2 based on the observational data for the past five years (2008～2012) in 10 meteorological offices (Sapporo, Aomori, Akita, Morioka, Yamagata, Sendai, Niigata, Nagano, Toyama, Kanazawa) located in heavy snowfall areas. Wind velocity (u_z) is converted from the value (u_a) measured by an anemometer installed at height a (m) above the snow surface using the logarithm rule for perpendicular distribution of wind velocity (Kondo,2000) and setting z at 2 m as indicated in the previous study (Pellicciotti et al.,2008). Although snow depth Ds at an observation point is needed at this time, Ds is computable from four observation data (refer to Section 5.1). Moreover, local atmospheric pressure AP was computed from temperature Ta and the altitude of the observation point based on the sea-level atmospheric pressure reported by weather government offices (Japan Meteorological Agency,2002). Water vapor pressure e_x was computed from Ta and rh (Meteorological Society of Japan,1996). The saturation water vapor pressure at snow surface temperature e_0 was estimated from Ta of the observation point using the approximate *Teten's* expression (Kondo,1994).

(3) Heat content of liquid precipitation Q_P

The wet-bulb temperature used by in equation 5 was computed from temperature Ta, relative humidity rh, and atmospheric pressure of the observation point AP using the expression of *Sprung* (Japan Meteorological Agency,2002). Moreover, as for precipitation Pr rain/snow distribution was performed from the temperature Ta measured when the rainfall was observed. In this research, the precipitation observed when Ta was below 0 ℃ was categorized as snowfall and that observed when Ta was over 0 ℃ was categorized as rain.

As mentioned above, using the method proposed this time, each of the elements shown in equation 1 can be determined from four observation data (temperature, precipitation, wind velocity and day light hours) which are obtained by AMeDAS etc. (Tbl. 3).

4.3 Result of estimations of snowmelt

In order to investigate the degree of difference between the quantity of heat for snowmelt Q_M calculated from the heat balance method shown in Section 4.1 considered to be a true value and Q_M obtained by the presumed model (refer to Section 4.2), both of the Q_M s were computed from the observational data at Shiozawa Snow Testing Station (the heat balance budget method needs seven types of observation data shown in Chapter 3 and the presumed model does four observation data shown in Section 4.2.) and were compared (Fig. 3). A total of 1689 hours were available for analysis (from January 6 to April 25 in 2011) which were the data without snow accretion to the measurement apparatus Fig. 3 shows snowmelt at the snow surface M (mm) converted from QM using the results from the above calculation.

Although in both cases there was a maximum difference in *Ms* of 3.3 mm/h, there was such a strong correlation that the coefficient of determination was 0.87, and the root-mean-square error (RMSE) over the true value was 0.5 mm/h. Moreover, comparing the integrated value of *M* during the observation, the true value was 1202 mm and the value acquired from the presumed model was 1266mm, and this result shows both were in agreement in general. As mentioned above, it turned out that the presumed model created by this research can estimate *M* without the use of the heat balance method which needs many observation data.

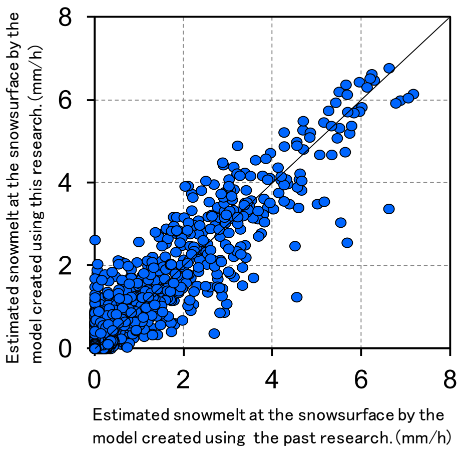

Fig. 3: The result of the estimation of the outflow from under the snowpack

5. DEVELOPMENT OF A MODEL FOR ESTIMATING SNOWMELT INFILTRATION PAGE IDENTIFICATION & PAGE NUMBERING

In order to reproduce the phenomenon of snowmelt infiltration, it is necessary to consider the influences of heat loss (refer to Section 5.1.) and time delay (refer to Section 5.2.). This chapter describes the snowmelt infiltration model created on the basis of weather/outflow observations and the results of previous studies.

5.1 Development of a model for estimating the characteristics of accumulated snow

Even if snow melt at the snow surface, when there is a snow layer below 0 ℃ in the snowpack, a part or all of the quantity of heat is used for rising the

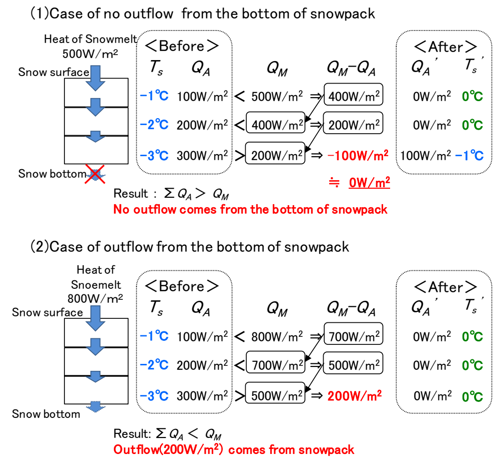

Fig. 4: Method for estimating snow temperature and outflow

temperature of the snow pack, and melting water could not reach the bottom of snowpack. As a result snowmelt at the snow surface *Ms* and outflow from the bottom of snowpack *Mb* are not necessarily in agreement. Consequently, in order to estimate *Mb* with sufficient accuracy, it is necessary to compute the loss of heat for fusion (called heat loss). In addition, in case all layers of snowpack are 0 ℃, the quantity of heat loss is 0 W/m^2.

In this research, in order to compute heat loss temperature, "the snow coverage quality model" which estimates physical-property values of a snow layer (one layer of snow is formed in 1 hour) such as temperature of each snow layer, snow depth, density, weight etc. from four observation data. This model can estimate snow temperature Ts in consideration of heat loss, and outflow from snowpack M_b by adding Q_M to the input value of the past viscous compression model (Endo et al.2004)(Suizu,2002). The calculation method of *Ts* and M_b examined in this research is as follows. First, we *calculate* snow temperature of each layer from the surface to the bottom using temperature *Ta* (Suizu,2002). Next, in order to compute heat loss, the quantity of heat required for raising the temperature of each layer to 0 ℃ is calculated from equation 6.

$$Q_A = C_i w T_s / 3.6 \tag{6}$$

where C_i is the specific heat of ice (2.1×10^3 J/℃ /kg), and w is the mass of each snow layer (kg/m^2). The difference in heat loss of each snow layer Q_A was calculated by the heat of fusion Q_M which the infiltrating snowmelt contained from the surface to the bottom of the snowpack. Then the heat loss of each snow layer was calculated in consideration of the heat of fusion (Fig. 4). The heat of fusion in consideration of heat loss Q_M' was obtained by deducting the amount of heat of fusion Q_M from the integrated value of the heat loss of each snow layer computed by this series of calculations. In this model, even if snow melted at the snow surface when Q_M was smaller than, M_b was computed at 0mm since the heat of fusion is used to obtain the rise in Ts. In this research, M_b was continuously *estimated* by repeating the abovementioned calculation every hour over a whole winter. In addition, in this calculation process, Ts' in consideration of heat loss can be found by substituting Q_A for equation 6.

5.2 Development of a model for estimating accumulated snow

When rain and snowmelt infiltrate thorough snowpack, we must consider the influence of the storage effect i.e., the problem of "delay time" process. Delay time is the time lag between snow melting on the snow surface until it reach the bottom of the snowpack. This influence cannot be disregarded in the estimation of the outflow from the bottom of snowpack in units of hours. In a recent study (Nakatsugawa et al.2004)(Matsumoto et al.2010), assuming the infiltration of snowmelt through saturated snow layer, the outflow from the snowpack $M(t)$ is estimated with the delay time (t) according to the Darcy's law (equation 7). The research in question also used this technique.

$$M_b'(t) = M_b'(t-1)exp(-1/k_0) + M_b(t) + P_r(t) - \{M_b(t) + P_r(t)\}exp(-1/k_0) + M_g(t) \qquad (7)$$

Where $M_b'(t\text{-}1)$ is the outflow from the snowpack 1 hour before the time (t) (delay time is taken into consideration), k_0 is the coefficient of storage which expresses the delay time, k_0 and D_s are outflow and precipitation in time t (without considering delay time), respectively. Mb is the amount of snowmelt at the bottom of the snowpack (snowmelt generated by ground warmth), referred to as 0.075 mm/h (Izumi,1983) throughout this research. It is known that delay time is dependent on snow depth or the structure of the snow layer. And in this research, k_0 was given as a function of snow depth D_s from the result of the weather/outflow observation in the Shiozawa Snow Testing Station. In addition, at the present stage, it is difficult to presume the structure of snow layer with sufficient accuracy, and there are many unknown variables in the relationship between the structure of the snow layer and the delay time. For this reason, the influence of snow layer structure on delay time was denoted by functions of k_0 and D_s. When obtaining the functions of k_0 and Ds, it is considered that 24 hours are one snow melting event. And the period of the event is ten days during which the estimated outflow of 24 hours k_0 and Ds the observed outflow of 24 hours k_0 and Ds are mostly in agreement and daily variation is clear. Next, k_0 and Ds, which are the input values for each time were substituted in equation 7 to obtain.

After this, k_0 was sought for every snowmelt event by trial and error until the smallest integrated value of the square error of the calculated k_0 and D_s the measured, obtained from a lysimeter, was found. The relation of k_0 and D_s calculated by the above method is shown in Fig. 5. In this Figure, it can be observed that the longer the penetration time is, the larger k_0 is, and that when D_s exceeds 1.5 m, k_0 becomes remarkably large. Therefore, in this research, it was presupposed that the relation of k_0 and D_s is expressed with an exponential function as shown in the equation 8 and equation 9 (Nakatsugawa et al.,2004.)

$$D_s > 0.5\ (\text{m}),\ k_0 = 1.654exp(1.143\ D_s) \qquad (8)$$

$$0.5 \geqq D_s \geqq 0\ (\text{m}),\ k_0 = 1.654 \qquad (9)$$

In addition, since k_0 may be subject to not only D_s but the snow layer structure etc., it is also assumed that k_0 is changing depending on the area or years. Therefore, continuous examination about how to give k_0 and the applicable condition of equation 8 is required.

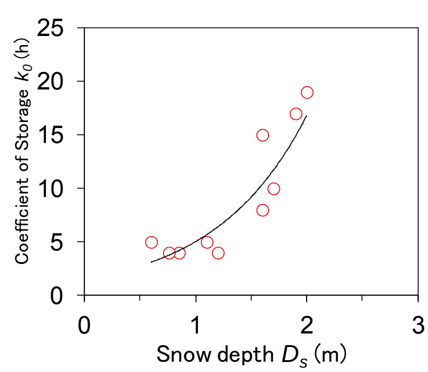

Fig. 5: The relationship of k_0-D_s observed at the Shiozawa Snow Testing Station

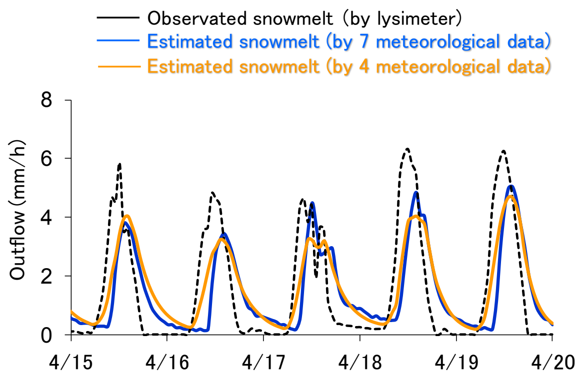

Fig. 6: Outflow from under the snowpack at Siozawa

6. RESULT OF ESTIMATION OF THE OUTFLOW FROM UNDER ACCUMULATED SNOW

According to the estimation procedure shown in Fig. 1, The outflow *Mb'* computed from a series of models shown in Chapter 4 and Chapter 5 was compared with actual measurements of *Mb'* obtained from observation data from the Shiozawa Snow Testing Station. As a result, the estimated peak value of Mb and the appearance time of the peak showed the proximity to the observed value actually (Fig. 6). Fig. 7 shows the result of the comparison between the estimated values and the observed values during the whole observation period. Although at peak level, both values have a difference of 4.3 mm/h, the root-mean-square errors (RMSE) over the actual measurement are 0.5 mm/h, and both values correlate well. Estimating Mb with not only the estimated model of snowmelt at the snow surface but also the infiltration model of the snowmelt have been created in this research, the RMSE of Mb (estimated value) was decreased by about 45%, compared with the presumed model which infiltration process is not taken into consideration.

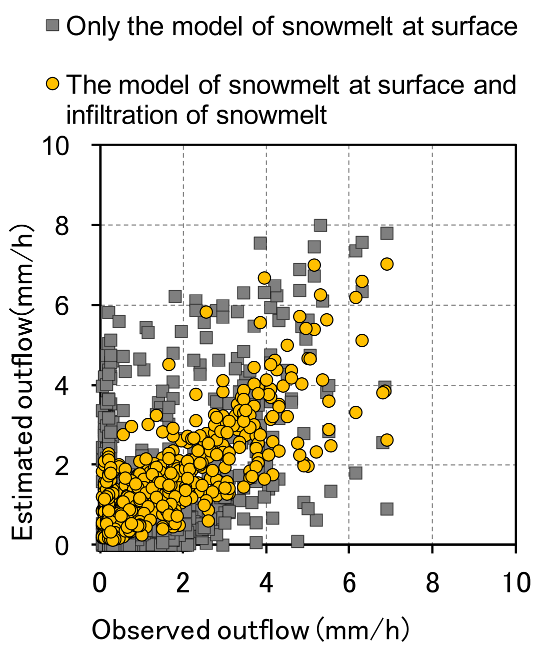

Fig. 7: The observed and estimated outflow from under the snowpack at Siozawa

7. EXAMING APPLICABILITY OF THIS ESTIMATION METHOD FOR ANOTHER AREA

To examine applicability of this estimation method for another area, observation was made at Iwamizawa in 2013. Iwamizawa is about 800km north from Siozawa Testing Station. And we estimate the outflow from the snowpack by these models. Fig. 8 shows the result of the comparison between the estimated values and the observed values in Iwamizawa and Siozawa. As compare with Siozawa, in Iwamizawa, it is cold and precipitation is small, and there is little outflow. Although at peak level, both values have a difference of 2.2 mm/h, the root-mean-square errors (RMSE) over the actual measurement are 0.4 mm/h, and both values are as well as the values of Siozawa.

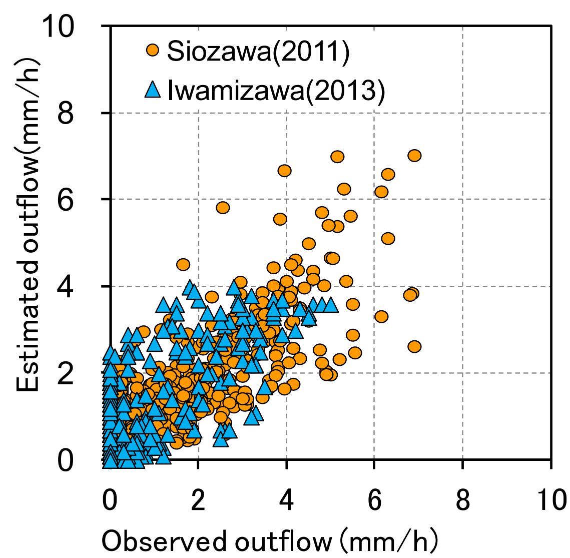

Fig. 8: The observed and estimated outflow from under the snowpack at Iwamizawa and Siozawa

The estimation method proposed in this paper makes it possible to estimate the outflow from the bottom of the snowpack per hour from only four types of observation data (temperature precipitation, wind velocity, and daylight) collected from AMeDAS observation points etc. which can be obtained easily, and the time resolution of the estimate is better compared to the past degree day method. In addition, by including the snow coverage quality model in the estimation process, the influence of snow temperature could be taken into consideration and the rain and thaw phenomenon accompanied by a temporary temperature rise in the middle of winter could also be evaluated. However since many underestimated or overestimated points are observed in the actual measurement as shown in Fig. 7 and Fig.8, the continuous examination of the estimation of snow melt by the simplified heat balance model we made or the method of setting the coefficient of storage is required.

8. CONCLUSION

This research examined a method for estimating outflow from under a snowpack which is closely related to the generation of a full depth avalanche. The method proposed in this paper makes it possible to estimate the outflow from under the snowpack per hour from four types of observation data (temperature, precipitation, wind velocity, daylight) collected from nearby AMeDAS points. For this reason, its application to railroad disaster prevention (for example, a point where the observation of the outflow from the snowpack is difficult because of problems such as inaccessibility due to surrounding environment) is expected.

From now on, while aiming at the improvement and extension of the estimated method, we advances analysis about the relation between the outflow and the stability of the snowpack that is the danger index of a full depth avalanche. And we would like to establish a stability assessment method of snowpack on the slope. In addition, further research aims to explore the application of these methods to earth-and-sand collapse, etc.

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