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<http://dx.doi.org/10.1016/j.coldregions.2009.05.004>

## Assessment of snowmelt triggered landslide hazard and risk in Japan

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## 1 **Abstract**

2 This study uses a probabilistic model based on multiple logistic regression analysis to  
3 evaluate landslide occurrence on natural terrain due to snowmelt in Japan. The evaluation  
4 concerns several physical parameters such as hydraulic parameters, geographical parameters  
5 and the geological parameters which are considered to be influential in the occurrence of  
6 landslides. Hydraulic gradient is the hydraulic parameter, which includes the effect of  
7 snowmelt. To estimate snowmelt and associated infiltration in light, average and heavy snow  
8 years, a widely used Snow Water Equivalent model (SWE) is used. Using the constructed  
9 spatial data-sets, a multiple logistic regression model is applied and landslide susceptibility  
10 maps are produced showing the spatial-temporal distribution of landslide hazard probabilities  
11 over Japan using 1km×1km resolution grid cells. The results show that, over 95% landslide  
12 hazard probability exists in the mountain ranges on the western side of Japan (the Japan Sea  
13 side), the Hokuriku region, and the Tohoku region. The developed landslide hazard  
14 probability map is verified using the past landslide events in the Aizu region of Fukushima  
15 prefecture, located in a landslide prone region. Verification proved that, areas identified as  
16 high risk areas (having over 90% landslide hazard probability in numerical modeling) show  
17 87% agreement with observed landslides in the Aizu region. In addition, the economical  
18 damage due to landslides is discussed taking road damages by landslides into account. The  
19 developed landslide hazard probability maps and economical damage maps will assist  
20 authorities, policy makers and decision makers, who are responsible for infrastructural  
21 planning and development, as they can identify landslide-susceptible areas and thus decrease  
22 landslide damage through proper preparation.

23

24 **Key words:** Landslide, Hazard maps, Probabilistic model, snowmelt, Risk management

1 **1. Introduction**

2

3 Japan has one of the heaviest snowfalls in the world, and snowfall plays an important role in  
4 the water resources of Japan (Kazama and Sawamoto, 1995). A great deal of irrigation for  
5 paddy fields is needed during spring seasons with less rainfall and snowmelt provides this.  
6 Snowfall contributes substantially to water resources but heavy snowfall can result in severe  
7 damage to infrastructure. Heavy snowfall creates hazards for humans through the destruction  
8 of buildings due to snow load, damage to electricity lines and hindering traffic. In the winter  
9 of 2006, for example, many casualties were recorded due to traffic accidents and the damage  
10 to homes caused by heavy snow (Ministry of Land, Infrastructure, and Transportation, 2007).  
11 In addition, snowmelt also leads to some disasters such as landslides, avalanches, and floods.  
12 Previous investigations show that many landslides have been shown to occur during snow  
13 melting periods (Aoyama, 1984; Ogawa et al, 1986; Maruyama and Kondou, 1998; Matsuura  
14 et al, 2003; Maruyama and Takeshi, 2004). The heavy snow in 2006 produced many  
15 landslides during snow melting period (Feb- March 2006) in various parts of Japan (Sato,  
16 2006). In addition, several landslides which were triggered by snowmelt were reported  
17 including famous the Shiidomari landslide of September 1999, the Katanoo landslide of  
18 January 2003 (Ayalew et al, 2005a; Ayalew et al, 2005b). Therefore, heavy snow areas  
19 should be evaluated for not only proper water resource management, but also disasters due to  
20 snowfall, as well as disasters owing to snowmelt, to maintain a safe and comfortable  
21 environment. Also, the areas that are particularly at risk for landslides should be identified so  
22 as to reduce the probability of damage in the region. In addition, global warming and climate  
23 change research shows that climate change will lead to a quick melt of the snow cover in  
24 Japan in the future (Inoue et al, 2002; Akazawa et al, 2005; Rikiishi, 2006). Therefore, it is

1 vital to understand the relationship between the present snow condition and snowmelt  
2 disasters in order to consider the future problem posed by global warming.

3 There is much research on landslide hazard evaluation; in particular, Guzzetti *et al.* (1999)  
4 have summarized many cases of landslide hazard evaluation studies. In the literature there  
5 have been numerous studies involving landslide hazard evaluation and they concerned  
6 different causes and used different approaches; Geological hazards triggered by earthquake  
7 shaking, rainstorm, rapid snowmelt and human activity (Han et al, 2007). Only few research  
8 available on snowmelt induced landslide hazard assessments (Guzzetti et al, 2002;  
9 Gokceoglu et al, 2005; Naudet et al, 2008). Shortage of snowfall observation stations and  
10 difficulty in developing spatial distribution of snowmelt induced landslides may lead to lack  
11 of research studies. The Japanese meteorological agency attempts to quantify snowfall over a  
12 wide area with one observation point at every 400 km<sup>2</sup>, referred to as Auto Meteorological  
13 Acquisition Data System (AMeDAS). However, no observation points are located in the high  
14 elevation regions which suffer the heaviest snowfalls. Remote sensing is an effective tool that  
15 can be used to estimate the size of snow-covered areas and to make detailed estimates of the  
16 amount of snowfall (Koike *et al.*, 1985; Kazama and Sawamoto, 1995; Derksen *et al.*, 2000).  
17 Numerous studies have shown that remote sensing tools are capable of determining snow  
18 depth and snow amount in localized areas (Tait, 1998; Koenig and Forster, 2004; Dong, *et*  
19 *al.*, 2005). Also, numerical simulations can express temporal variations in the snow depth  
20 and snow amount (Yamazaki *et al.*, 1999; Inoue and Yokuyama, 2003).

21 In the literature there have been numerous studies involving landslide hazard evaluation and  
22 they used different assessing approaches; deterministic and statistical approaches. Wu and  
23 Sidle, 1995; Gokceoglu and Aksoy, 1996; Atkinson and Massari, 1998; Yilmazer et al, 2003;  
24 Xie et al, 2007 presented some deterministic approaches using geotechnical methods,  
25 whereas, Temesgen *et al*, (2001); Lee and Min (2001); Ohlmacher and Davis (2003); Westen

1 *et al.*, (2003) used statistical approaches. Also some studies compared the assessments from  
2 statistical approaches and deterministic approaches and discussed their advantages and  
3 disadvantages (Calcaterra *et al* 1998; Aleotti and Chowdhury, 1999; Lee *et al*, 2008).  
4 Deterministic approaches are based on slope stability analyses, and are only applicable when  
5 the ground conditions are fairly uniform across the study area and the landslide types are  
6 known and relatively easy to analyse (Dai *et al.*, 2001). Statistical approaches on the other  
7 hand are indirect hazard mapping methodologies that involve statistical determination of the  
8 combinations of variables that have led to landslide occurrence in the past. Probability is the  
9 key issue in the statistical analysis. Also, the probabilistic method is suitable and can be used  
10 over a large area where numerous natural slopes exist (Refice and Capolongo (2002);  
11 Guzzetti *et al*, (2005); Zolfaghari and Heath, (2008); Shou *et al* (2008). Thus, the use of  
12 probabilistic methods has become an important aspect in assessing landslide hazard maps  
13 where the probability, location, and frequency of future landslide can be predicted. It  
14 provides potential to assess the landslide hazard in a given area in terms of probability of  
15 occurrence of a potentially damaging landslide event within a specified period using  
16 probabilistically. In this study, a probabilistic analysis approach is implemented in order that  
17 we can evaluate the landslide hazard probability due to snowmelt over whole of Japan, with  
18 consideration of snowmelt as main external parameter. Therefore, this assessment will be a  
19 vital subject for authorities, as they can assess and predict landslide-susceptible areas and  
20 thus decrease landslide damage through proper preparation, and it assists decision makers  
21 who are responsible for infrastructural development and environmental protection.

22

## 23 **2. Methods and Materials**

24 Many researchers have tried to understand the factors affecting landslide hazards.  
25 Geographical and geological factors had been considered using aerial photographs, and

1 remote sensing data (Kojima *et al.*, 2003; Tarolli and Tarboton, 2006). However, hydrology  
2 conditions, especially rainfall and snowmelt condition should be considered with landslide  
3 hazard evaluations (Richard *et al.*, 1996; Jochen *et al.*, 2004; Temsgen, et al, 2001).  
4 In this study, several factors affecting landslide hazards are taken into account and  
5 categorized into groups; hydraulic factors, geological factors and geographical factors.  
6 Change in hydraulic gradient due to snowmelt is considered as hydraulic factors. To estimate  
7 the snowmelt and associated infiltration, the Snow Water Equivalent (hereafter referred to as  
8 SWE) model developed by Kazama et al (2008) is used in this study. It produces the amount  
9 of snowmelt which used as the input for infiltration analysis to estimate hydraulic gradient.  
10 The relief energy, slope gradient and topography are considered as the geographical factors.  
11 Four commonly available geological types in Japan; colluviums, paleogene sedimentary  
12 rock, new tertiary sedimentary rock, and granite represent the geological factors. All these  
13 data are obtained in digital format and data resolution is 1km×1km. Therefore, the results of  
14 landslide hazard probability are portrayed in a 1km×1km resolution map. Taking landslide  
15 induced damages to infrastructure in landslide prone areas into account, an economic damage  
16 assessment is conducted. Finally, the landslide hazard probabilities (hazard index) are  
17 combined with economic damage evaluations (economic index) to develop the landslide  
18 hazard risk assessment.

19

## 20 **2.1 Hydraulic factors**

21 Hydraulic gradient is an active property in initiation of landslides. Increase of hydraulic  
22 gradient cause piping phenomenon and sediment flow on a slope (Moriwaki et al, 2006;  
23 Sultan, et al, 2007). Change in hydraulic gradient as a result of infiltration of snowmelt water  
24 is used as the main parameter to reflect the hydraulic condition in this study. The hydraulic  
25 gradient ( $\Delta h/L$ ) is derived from the phreatic line obtained by unsaturated infiltration

1 analysis based on Richards equation (Richards, 1931; Ross, 1990), using soil data, slope  
2 angle and snowmelt (snow water equivalent) as the main input data as shown in Fig 1. Two  
3 numerical models are used to evaluate hydraulic gradient. The SWE model is used to  
4 estimate snowmelt and an infiltration analysis is used to estimate the hydraulic gradient.

5

### 6 **2.1.1 Snowmelt estimation**

7 Landslide records in Japan show that, in several cases, landslide triggered by snowmelt water  
8 (Ayalew et al, 2005a; Ayalew et al, 2005b). Therefore, snowmelt in heavy snowfall events is  
9 in the main interest. Modified Snow Water Equivalent (SWE) model developed by Kazama  
10 et al (2008) is used to estimate the snowmelt amount in several snowfall events such as light  
11 snowfall events, average snowfall events and heavy snowfall events.

12 The SWE model is composed of snowfall and snowmelt. This simulation was carried out at a  
13 1.1 km by 1.1 km resolution, similar to the AVHRR remote sensing data resolution.  
14 Temporal changes in the snow water equivalent can be expressed as follows (Niwa and  
15 Moritani, 1990);

16

$$17 \quad \frac{d}{dt}(SWE) = SF - SM \quad (1)$$

18

19 Where SWE is the snow water equivalent (mm), SF is the daily snowfall at each pixel  
20 (mm/day), and SM is the snowmelt rate (mm/day). Since we have dealt with a large-scale  
21 process and have neglected snowdrift, it was assumed that the rainfall was immediately  
22 drained outside the snow-pack after the maximum possible snow density was achieved.

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24 Degree-day method was selected to estimate snowmelt. The degree-day equation is expressed  
25 in the following equation:



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$$SM = K \times T \tag{2}$$

where  $K$  is the degree-day parameter ( $\text{mm}/^{\circ}\text{C}/\text{day}$ ) and  $T$  is the mean daily temperature ( $^{\circ}\text{C}$ ). If  $T$  is less than 0, snowmelt is not evaluated and the negative value is ignored. The advantage of this method is that the equation has only a one degree-day parameter. When correlating the snow area estimated by the degree-day method with a satellite image, it is easy to determine the optimized degree-day parameter.

This numerical model required precipitation, temperature and elevation data for the snow estimation. Elevation data effects the temperature distribution depending on the lapse rate. A DEM (digital elevation model) is used to obtain elevation data with a ground resolution of 250 m by 250 m in this study. Distributions of the climatic data are interpolated using observation data depending on elevation. Also, snow covered area maps made by remote sensing data are used to calibrate the model parameters. In addition, snow cover maps in time series are made from satellite images. Tohoku University provides JAIDAS (Japan Image Dataset) via the Internet, which covers eastern and western Japan with information of all channels of AVHRR/NOAA. JAIDAS prepares two image sets per day. The dataset resolution was 1.1 km in the Mercator projection and was automatically transferred to physical values of albedo and brightness temperature for channel 1 and channel 2, and channel 3 to channel 5, respectively. There are some disagreements in these images due to corrections in the coordinate systems. In such situations, we shifted the satellite images manually to adjust the satellite images to the appropriate coordinate system.

This simulation was carried out at a 1.1 km by 1.1 km resolution, similar to the AVHRR resolution and the output of snowmelt data was in 1.1km×1.1km. Since other parameters of infiltration analysis (soil data and topography data) are in 1km×1km resolution, the snowmelt

1 results are converted to 1km×1km resolution to input to infiltration model. The estimated  
 2 snowmelts are used as the main hydraulic input for the infiltration analysis.

3

#### 4 **2.1.2 Infiltration analysis**

5 Unsaturated infiltration analysis is used to obtain the change in hydraulic gradient due to  
 6 snowmelt ( $\Delta h/L$  in Fig 1). In addition to snowmelt data obtained from SWE model, soil  
 7 type data and slope angle data are used for the infiltration analysis, which is obtained from  
 8 the Digital National Land Information data (2001) published by Geographical survey  
 9 institute and Ministry of land, Infrastructure Transport and Tourism, Japan). The governing  
 10 equations and iteration steps for the infiltration analysis are as follows:

11 First the water volume content  $\theta$  can be estimated as

$$12 \quad \frac{\partial \theta}{\partial t} = - \left( \frac{\partial V_x}{\partial x} + \frac{\partial V_z}{\partial z} \right) \quad (3)$$

13 Where  $\theta$  is the water volume content,  $t$  is time step,  $V_x$  is the velocity in horizontal direction,  
 14 and  $V_z$  is the velocity in vertical direction.

15 The flow velocities ( $V_x$  and  $V_z$ ) is obtained by of Darcy's equation (Eq. 2).

$$16 \quad \begin{aligned} V_x &= -K_x \frac{\partial h}{\partial x} \\ V_z &= -K_z \frac{\partial h}{\partial z} \end{aligned} \quad (4)$$

17 Where  $h$  is the total hydraulic head,  $K_x$  is the unsaturated hydraulic conductivity in horizontal  
 18 direction and  $K_z$  is the unsaturated hydraulic conductivity in vertical direction.

19 The total hydraulic head  $h$  is the sum of the hydraulic pressure head  $\psi$  and elevation head.

20 The elevation head can be estimated using horizontal and vertical length components ( $L_x$  and

21  $L_z$ ), as  $-L_x \sin \alpha - L_z \cos \alpha$

1 Therefore total head is

$$2 \quad h = \psi - L_x \sin \alpha - L_z \cos \alpha \quad (5)$$

3 Combining equations (1), (2) and (3), two dimensional hydraulic head can be obtained as  
4 (Richards, 1931)

$$5 \quad C \frac{\partial \psi}{\partial t} = \frac{\partial}{\partial x} \left( K_x \frac{\partial \phi}{\partial x} \right) + \frac{\partial}{\partial z} \left( K_z \frac{\partial \phi}{\partial z} \right)$$
$$6 \quad C \frac{\partial \psi}{\partial t} = \frac{\partial}{\partial x} \left( K_x \frac{\partial \psi}{\partial x} - K_x \sin \alpha \right) + \frac{\partial}{\partial z} \left( K_z \frac{\partial \psi}{\partial z} - K_z \cos \alpha \right) \quad (6)$$

7

8 Where  $C$ , ( $C(\psi) = \partial \theta / \partial \psi$ ) is the specific moisture capacity. Specific moisture capacity  $C$   
9 can be obtained by the gradient of the soil moisture characteristic curves (Gosh 1980; Ahuja  
10 et al, 1985) and the corresponding values for soil types which are commonly available in  
11 Japan are obtained from the soil moisture characteristic curves developed by Kawakami,  
12 (2003).

13

14 To solve this equation, two relationships have been used.

15 1) Relationship between unsaturated hydraulic conductivity  $K$  and water volume content  $\theta$

$$16 \quad K_x = K_{s_x} \left( \frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^\beta$$
$$K_z = K_{s_z} \left( \frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^\beta \quad (7)$$

17 Where  $\beta$  is soil characteristic value

18 2) Relationship between pressure head  $\psi$  and water volume content  $\theta$  (Bruseart 1968).

$$19 \quad \theta = (\theta_r - \theta_s) \left( \frac{\psi'}{\psi_0} + 1 \right) \exp \left( - \frac{\psi'}{\psi_0} \right) + \theta_r \quad (8)$$

1 Where  $\theta_s$  is the saturation water volume content,  $\theta_r$  is the residual water volume content and  
2  $K_s$  is the instauration hydraulic conductivity. These parameters can be obtained from the  
3 literature (Kawakami 2003). Four soil types (gravel, sand, silt and clay) are taken into  
4 account for the infiltration analysis and Table 1 shows the properties of each soil type.  
5 Combining equation (4), equation (5) and equation (6), an iteration process is employed to  
6 solve these equations where  $\psi_0$  is initial condition and  $\psi'$  is the saturation condition in each  
7 iteration step. The convergent value of hydraulic head is used to estimate the hydraulic  
8 gradient as  $\Delta h/L$

9

## 10 **2.2 Geographical factors**

11 Geographical properties of the slope effectively affect the probability of landslide hazards.  
12 To represent geographical features, relief energy is utilized as an input for probability model.  
13 Relief energy is an index that could show the complexity of geographical features  
14 considering the active development of landform. Derbyshire (1995) has presented a series of  
15 new equations expressing the loss of potential energy of the landslide mass in relation to the  
16 relative relief energy and the pressure energy input in the form of rainfall, based on over 200  
17 landslides in the Gansu Province, China. As defined by Crescenzo (2005), relief energy of a  
18 slope is the difference in height between the divide of the landslide slope and the first break  
19 of slope at the foot of the slope while the potential zone of triggering is the difference in  
20 height between the altitude of the ridge and that of the crown. Therefore, in this study relief  
21 energy is defined as the elevation difference between the lowest and the highest elevation in  
22 each grid cell and the relief energy value for each 1km×1km resolution grid cell is estimated  
23 using the digital elevation model data of the study area obtained from National-land  
24 information database (2001).

25

### 1 **2.3 Geological factors**

2 Four mostly common geological properties are considered as geological parameters for the  
3 study; colluviums, tertiary sedimentary rock, and granite. Tertiary sedimentary rock is  
4 divided to two sub groups as new tertiary sedimentary rock and paleogene tertiary  
5 sedimentary rock considering the difference of geological properties. Geological property  
6 data are also obtained from the digital national land information database (National-land  
7 information data, 2001)

8

### 9 **2.4 Historical landslide observations**

10 A key assumption using this approach is that the potential (occurrence possibility) of  
11 landslides will be comparable to the actual frequency of landslides. Historical landslide  
12 hazard data for Aizu region in Fukushima prefecture, where lot of landslide damages are  
13 occurred in snow melting season in 2000, are used to compare the developed landslide  
14 hazard maps and actual landslides. From 21st March to 28th March, 2000, 61 landslides were  
15 occurred due to the snowmelt in Aizu region (over 5420.69 km<sup>2</sup> area). This is the maximum  
16 number of landslides in recent history. These data were obtained from Kitakata and  
17 Wakamatsu Construction Office authority in Fukushima prefecture and converted to vector-  
18 type spatial landslide hazard map of 1km×1km resolution using the ARC/INFO GIS software  
19 (Sediment control division, 2001) of Fukushima prefecture). Fig 2 shows the observed  
20 landslide locations in Aizu region.

21

### 22 **2.5 Economic damage data**

23 Taking economical damage of landslides into consideration, an economic damage assessment  
24 is carried out. Damages to infrastructure in landslide prone areas; mainly highways and roads  
25 are considered. Highways and roads are the main infrastructure located in mountain regions.

1 It is the most important link to connect these mountainous areas to urban areas. Landslide  
2 damages the roads in mountain areas and it leads to loss an extensive economic worth.  
3 Therefore, damages to roads due to landslides are estimated taking three factors into  
4 consideration; cost for repair and renovate the damaged roads, additional time and resources  
5 lost to use alternative roads. The cost depends on the length of the damaged part of the road  
6 and road category. Therefore the economic assessment model needs data on the distribution  
7 of road density and category of roads. Road density data is obtained from National Land  
8 Information Data (2001). Road category data is obtained reference to the definition of  
9 Landslide Economic Damage Manual (2003). According to the landslide economic damage  
10 manual, road category is defined based on road width. Roads wider than 13m ( $W > 13m$ ) is  
11 defined as expressways and national roads. Road wide between 3m to 13 m ( $3m < W < 13m$ )  
12 are defined as general roads. Narrow roads (width is less than 3m) are defined as rural roads  
13 or gravel roads.

14

### 15 **3. Selection of snowfall events: Identification of heavy, light and average snow years**

16 Results of SWE model is used to identify snow condition to select the heavy snowfalls and  
17 extreme snowmelt events to use as the main input for infiltration analysis. AVHRR/NOAA  
18 satellite images are the main data source for SWE model. We used 16 years (1990-2005)  
19 AVHRR/NOAA satellite image data from Japan Image Dataset (JAIDAS). Using these data  
20 the SWE model produces snow accumulation and snowmelt amounts in each year over  
21 Japan. Based on the estimated SWE and snowmelt results, the annual maximum weekly  
22 snowmelt for each year is estimated as shown in Table 2. It clearly shows that snowmelt in  
23 year 2000 and 2005 are the heaviest snowmelt during the considered 16 years. Snowmelt in  
24 1990 is the smallest snowmelt. Rests of the years show average conditions.

1 For further investigations, temporal distributions of SWE for several selected years are taken  
2 into account (1990, 1999, 2000, 2004 and 2005). The distribution of average daily SWE over  
3 Japan from 1st January to 30th April in each year is shown in Fig 3. This distribution clearly  
4 shows that SWE in 2000 and 2005 show remarkable difference from other years. It has  
5 higher SWE throughout the winter. Therefore, year 2000 and 2005 are considered as heavy  
6 snow years. Also these two years show rapid reduction of SWE from early April indicating  
7 that these two years had high snowmelt at the end of the winter. This means in 2000 and  
8 2005, large snowmelt has occurred within a short period. Also Fig 3 shows very low SWE  
9 and gentle change with time in 1990. This resulted less snowmelt in 1990. The situation is in  
10 average condition for 1999 and 2004. Therefore, for the further discussions we define  
11 snowfalls as heavy snow years (year 2000 and 2005), light snow years (1990) and average  
12 snow years (1999 and 2004).

13

### 14 ***3.1 Spatial distribution of snowmelt***

15 After identifying heavy, light and average snow years, the SWE model is used to evaluate  
16 maximum weekly snowmelt throughout the Japan for each heavy, light and average snow  
17 years. Since SWE model resolution is 1km×1.1km, the results obtained from SWE model  
18 shows 1.1km×1.1km resolution maps for snowmelt maps. To input to infiltration model,  
19 these snowmelt maps are converted to 1km×1km resolution maps (Fig 4). These maps show  
20 that generally, the mountain range on the western side of Japan (Japan Sea side) has the  
21 highest snowmelt in all years. Especially steep mountain regions spread in these areas  
22 because mountains areas in receive the maximum snowfall during the winter. In heavy snow  
23 year (2000) the heavy snowmelt region has extended northward up to whole Hokkaido Island  
24 and southward up to the lower part of the Hunshu Island.

25

#### 4 Assessment of landslide hazard probability

After compiling the required data, a stepwise logistic regression model between landslide probability and the above mentioned physical parameters is constructed. The multiple logistic regression method is preferred over susceptibility analysis, since multiple logistic regressions allow forming a multivariate regression relation between a dependent variable and several independent variables. Also the logistic multiple regressions is easier to use than susceptibility analysis when there is a mixture of numerical and categorical regresses, because it includes procedures for generating the necessary dummy variables automatically (Hair et al., 1998). As many interesting variables are categorical in this landslide analysis, multiple logistic regression analysis is used and the regressions are formulated in the form of regression coefficient. Since hydraulic gradient is used as one temporal variable, multiple logistic analysis is useful to use kinetic data and to simulate predicted future data and temporal changes. In the analysis, the landslide hazard being described as an independent variable by the binominal distribution. For each geological type, the landslide hazard is described by the explaining variables such as hydraulic gradient and relief energy. The landslide hazard probability response variable is constructed as a logistic curve with multiple regressions, as expressed in Eq. (15)

$$\log\left(\frac{P}{1-P}\right) = \sigma_0 + \sigma_h hydY_h + \sigma_r reliefY_r$$
$$P = \frac{1}{1 + \exp[-(\sigma_0 + \sigma_h hydY_h + \sigma_r reliefY_r)]} \quad (9)$$

Where  $P$  is the probability of landslide occurrence,  $\sigma_0$  is the interception,  $\sigma_h$  is the coefficient of hydraulic gradient,  $\sigma_r$  is the coefficient of relief energy,  $hydY_h$  is the hydraulic gradient, and  $reliefY_r$  is the relief energy.



1 The results of the multiple logistic regressions expressing the relationships among hydraulic  
2 gradient and relief energy for each geological property are summarized in Table 3.  
3 As explained in probability equations, probability of landslide hazard for each geological  
4 type depends on two explaining variables; hydraulic gradient and relief energy. The  
5 distribution area of each geological condition is able to affect the probability of landslide  
6 hazard and distort the results because the geological features are not uniformly distributed  
7 over the area. Therefore, the probability analysis is separately constructed for four geological  
8 features: colluviums, paleogene sedimentary rock, new tertiary sedimentary rock, and  
9 granite. The developed logistic curves for four geological properties are presented in Fig 5.  
10 The rising position (position that the probability  $> 0$ ) and the slope angle of the logistic  
11 curves could display the risk of geological feature. When the rising position is lower, it gives  
12 higher risk. Also when the slope is steep, it gives high risk. Fig 5 shows that colluviums  
13 geological property shows the highest risk. Second highest is new tertiary sedimentary rock.  
14 The least risk geological property is granite. This order corresponds to the hardness of  
15 geological features. Then the developed probability model is applied to each 1km×1km grid  
16 cell employing the hydraulic, geological and geographical properties of each cell. This task  
17 produced the assessment maps showing the distribution of landslide hazard probability over  
18 whole Japan.

19

## 20 **5. Results and discussions**

21 The results of the probability model, the spatial distribution of landslide hazard probability  
22 based on snowmelt induced infiltration condition, geographical conditions and geological  
23 conditions of the area are portrayed on landslide hazard probability maps using Geographic  
24 Information System (GIS) technology. To evaluate the temporal changes, the probability is

1 estimated for changing hydraulic factors using three identified snow conditions; heavy snow,  
2 average snow and light snow years.

3 The developed snowmelt induced landslide hazard probability maps for light, average and  
4 heavy snow years are shown in Fig 6. The overall distribution of landslide hazard probability  
5 as well as comparison of the change in different snow conditions are highly important,  
6 because different snowmelt amounts correspond to heavy, average and light snow years  
7 dictates the time frames and design guidelines for countermeasures and it also show the order  
8 of priority in mitigation processes and financial fund allocations.

9 The developed landslide hazard probability maps clearly separate the high risk and low risk  
10 areas. The regions where the landslide hazard probability is greater than 95% are marked as  
11 high risk areas. Overall, the mountain range on the Japan Sea side shows the highest  
12 landslide hazard probability. In the case of light snow years, the Hokuriku region shows the  
13 largest landslide hazard probability, especially, Iide mountainous range (Niigata Prefecture),  
14 North West side of Echigo and Mikuni Mountainous ranges (Niigata Prefecture), and  
15 Boundary of Nagano Prefecture and Toyama Prefecture, which all show over 90%  
16 probability of experiencing landslides due to snowmelts.

17 In case of average snow year, the dangerous areas further expand from Hokuriku region to  
18 Tohoku region. Especially, remarkable increase of probability region is Dewa mountainous  
19 range which shows over 95% of landslide hazard probability. Dewa mountainous range  
20 distributes on the Japan Sea side of the Tohoku region. In addition, the regions having  
21 landslide hazard probability of 50% to 70% are scattered in the edge of mountain range. In  
22 addition, it is admitted also on the Pacific Ocean side of the Japanese Islands besides this  
23 region about generating landslide probability. These are, Akaiashi mountain range (boundary  
24 of Nagano Prefecture and Shizuoka Prefecture), and the East side of Kitakami mountain  
25 range (Iwate Prefecture).

1 In the heavy snow year, the dangerous area expands from Hokkaido to Chugoku region as  
2 Japan Sea side. Especially, some addition areas concentrate for over 95% probability such as  
3 Yamagata Prefecture, Aizu region in Fukushima Prefecture, Niigata Prefecture, and Ishikawa  
4 Prefecture. Moreover, it shows increasing probability from 5% to 25% in Shiga Prefecture  
5 and Kyoto Prefecture.

6 Overall, Fig 6 shows that landslide hazard danger increases during heavy snow conditions.

7 For each snow condition, the following areas are identified as high landslide hazard  
8 probability regions;

9 Light snow year- Hokuriku region

10 Average snow year- Hokuriku region and Tohoku region

11 Heavy snow year- West side of Japan (Japan Sea side)

12

13 These areas should be given priority for developing mitigations and countermeasures. Most  
14 of these high risk areas are relatively low populated areas. Therefore, the direct impacts on  
15 human lives and properties are less in most of the areas. Even though population densities  
16 are comparatively low, all these mountain ranges are supplied with a large amount of  
17 infrastructure especially highways and railways. Landslides damage the transportation  
18 infrastructures in these areas, especially, not only collapse of the roads and railways, the  
19 landslides blocks the roads and railways causing serious traffic problems during heavy  
20 rainfall periods.

21

### 22 ***5.1 Model verification with past events***

23 In many landslide susceptibility and hazard mappings, independent validation of statistical  
24 models for landslide hazard or susceptibility assessment is lacking (Remondo et al, 2003;  
25 Westen et al., 2003). In prediction modelling, the most important and the absolutely essential

1 component are to carry out a validation of the prediction results (Chung and Fabbri, 2003).  
2 One of the objectives of the present study is to perform such validation using recorded past  
3 landslide data.

4 Collected past landslide hazard data in Aizu region in Fukushima prefecture, where lot of  
5 landslide damages are occurred in snow melting season in 2000, are used to compare the  
6 developed landslide hazard maps and actual landslides (refer Fig 2). From 21<sup>st</sup> March to 28<sup>th</sup>  
7 March, 2000, 61 landslides were occurred due to the snowmelt in Aizu region (Sediment  
8 control division report, 2001)

9 Using the developed landslide hazard probability map, two main group of risk conditioned  
10 are defined as “landslide risk areas” and “no risk areas”. Areas having average landslide  
11 hazard probability of 90% or more are categorized as “landslide risk areas” and areas having  
12 landslide hazard probability less than 90% are categorized as “no risk areas”. The observed  
13 61 landslide locations are overlapped on landslide hazard probability map (Fig 7a). It shows  
14 that most of the landslides (43 landslides) are occurred in landslide risk areas (where  
15 landslide hazard probability is over 90%). Only few landslides (18 landslides) are occurred in  
16 no risk areas. This is 87% agreement.

17 If the threshold for “landslide risk areas” and “no risk areas” is reduced to 70%, Fig 7b shows  
18 that more than 90% of the observed landslides (55 out of 61) are located inside the “landslide  
19 risk areas”. Table 4 summarizes the number of observed landslides located in risk and no risk  
20 areas over Aizu region. Therefore for management point of view areas with landslide hazard  
21 probability with more than 70% should be taken into account when planning mitigation and  
22 countermeasures. Anyway as overall situation, the observed landslide records are well  
23 matches with the analytical results.

24

25

## ***5.2 Relationship between landslide hazard results and snowmelt***

Japan ministry of Land, Infrastructure, Transport and Tourism frequently monitors the municipal areas and heavy residential areas for landslide disasters (Disaster report 2004, 2005). Fig 8 shows the municipal areas identified as heavy disastrous areas by Japan ministry of Land, Infrastructure, Transport and Tourism during snowmelt season from 2000 to 2005. This includes the landslides in residential areas. It does not include landslides in forests or rural mountain areas. Table 5 summarizes time period which landslides were occurred in these heavy disastrous areas. This data clearly shows that most of the recorded snowmelt induced landslides in these frequently monitoring disastrous areas occurred in the spring season (usually at the end of March). Also this data shows that more landslides were occurred in these areas during heavy snow years; 2000 and 2005. In addition, the Ministry of Land infrastructure and Transport provides the information on all recorded landslides over whole Japan (Report on statistical water damages: 2000-2005, 2007). According to this report, the number of landslides (irrespective of the disaster level) during snow-melting season in each year is as shown in Fig 9. Fig 9 shows also the maximum number of snowmelt induced landslides was recorded in 2000. There were 89 snowmelt induced landslides recorded in 2000. The second maximum was in 2005. It was 59 landslides. This data shows that heavy snow years contribute for more snowmelt landslides.

## ***5.3 Contribution of weather condition to landslide disasters***

The other interested criteria is to find the relationship between snowmelt induced landslides and weather conditions; especially the atmospheric temperature. Fig 10 shows the relationship between snow depths versus precipitation and snow depths versus temperature for heavy snow years; 2000 and 2005 in Tajima city, in Fukushima prefecture. The precipitation and temperature data are obtained from the average of AMeDAS observations.

1 Precipitation is presented as either rainfall or snowfall (upward scale is rainfall and  
2 downward scale is snowfall).

3 Fig 10 shows that heavy snow accumulates from the end of February to the end of March and  
4 rapid snowmelt occurs from the end of March to the beginning of April in both years. The  
5 rapid snowmelt generates when heavy snow amount accumulates at the temperature rise  
6 period (the end of March to the early April). These heavy snows at the temperature rise  
7 period, generates lot of landslides. Especially in 2000, there was one heavy snow event at the  
8 end of March and followed by a temperature rising leading to high snowmelt amount within  
9 short period. It is interpreted that this heavy snowfall was caused in the end of March  
10 because the normal temperature at this time was below the freezing point. This abnormal  
11 heavy snowfall caused large snow melting long with a rapid temperature rise at the end of  
12 March 2000, because the temperature increased by 5<sup>0</sup>C immediately after the snowfall. These  
13 entire phenomenons leaded to create lot of snowmelt induced landslides in year 2000.  
14 Therefore abnormal weather changes are very critical, when considering landslide hazards in  
15 snowmelt periods. On the other hand, it is important to evaluate not only the heavy snow  
16 conditions, but also proceeding weather conditions when assessing snowmelt induced  
17 landslide hazards.

18

#### 19 ***5.4. Assessment of economical damages***

20 The economic damage is assessed taking road damages owing to landslide into account.

21 Three main factors are considered to estimate the economic damage by road damages due to  
22 landslides;

- 23 1. Cost to repair /renovate the roads
- 24 2. time lost when using alternative roads while road is damages
- 25 3. cost due to additional distance traveled when using alternative roads

1 The economic damage for each 1km×1km grid cell is obtained by multiplying the landslide  
 2 probability by the total road length in the grid cell and the economic value per unit length of  
 3 the road for repair, time loss and additional distance traveled as follows;

4

$$5 \quad Total\ Cost = (T_C + L_c + \sum L \times M_R) \times Probability \quad (10)$$

6

7 Where L is the total road length in each grid cell and  $M_R$  is the repair cost per unit road  
 8 length.  $T_C$  is the time loss and  $L_c$  is the cost to travel additional distance.  $T_c$  and  $L_c$  are  
 9 defined as follows;

10

$$11 \quad Cost\ of\ time\ loss\ (T_C) = \sum T_i \times (T_{m1} \times S - T_{m2} \times S) \quad (11)$$

12

13 Where  $T_i$  is the time value in monetary unit (yen/min),  $T_{m1}$  is the travel time (in minutes),  
 14 when travelers use alternative roads,  $T_{m2}$  is the travel time (in minutes), if the landslide does  
 15 not occur (original road is been used).  $S$  is the number of vehicles traveled.

16

$$17 \quad Cost\ of\ additional\ distance\ travelled\ (L_c) = \sum L_i \times (L_{m1} \times S - L_{m2} \times S) \quad (12)$$

18

19 Where  $L_i$  is the travel cost per unit distance in monetary unit (yen/m),  $L_{m1}$  is the distance  
 20 travels when use alternative roads,  $L_{m2}$  is the distance travels if the landslide does not occur  
 21 (original road is been used).  $S$  is the number of vehicles traveled.

22

23 Repairing cost ( $M_R$ ) is obtained from the Ministry of Land infrastructure and Transport (Cost  
 24 convenience analysis manual of the civil construction, 2003). This manual gives the repair  
 25 cost for expressway and national road is 103,000 yen/m, and the repair cost for public

1 highways is 77,000 yen/m. Also this manual gives the unit cost of time loss in monetary unit  
2 ( $T_i$ ) as 519.6 yen/hour per vehicle (8.66 yen/min.vehicle) and travel cost per unit distance in  
3 monetary unit ( $L_i$ ) as 6.24 yen/m. per vehicle. In addition the traffic data (average number of  
4 vehicles per day) published in traffic investigation result of Japan, by the Ministry of Land  
5 infrastructure and Transport (Traffic census, 2004), is used to estimate the average number of  
6 vehicles use the respective road.

7 The developed economical damage maps considering road damage distribution for light,  
8 average and heavy snow years is shown in Fig 11. In case of light snow year, the region with  
9 a potential road damage of over 500 million yen (heavy economical damage) is distributed  
10 along the main railway-tracks in the west part of Japan. According to the recent landslide  
11 observations, it is clear that these routes affected by several landslides over last few years.  
12 The overall distribution of road damages in a light snow year depict, areas having potential  
13 road damage of over 50 million yen are distributed as follow;

14 a) Roads locate in mountain range of the Ashio and the Kanto (Gunma Prefecture, Nagano  
15 Prefecture, Saitama Prefecture)

16 b) Roads locate in mountain range of the Mikuni and the Echigo (Niigata Prefecture)

17

18 During an average snow year, the areas having potential road damage of over 500 million  
19 yen (heavy economical damage areas) expand toward north and south along the main road  
20 network in the west side of Japan. During average snow years some regions which were in  
21 over 50 million road damage group move to heavy economical damage areas (potential road  
22 damage of over 50 million yen) as follow.

23 c) Distributed road in mountain range of the Ashio and the Kanto mountains (Gunma  
24 Prefecture, Nagano Prefecture, Saitama Prefecture)

25 d) Distributed road in Aizu region (Fukushima Prefecture)



- 1 e) Distributed road in Dewa mountain range (Akita Prefecture)
- 2 f) Distributed road in mountain range of Kiso and Ina (Gifu Prefecture)

3

4 In addition the areas having potential road damage of over 50 million yen expands towards  
5 west coast (Japan Sea side) and east coast (Pacific Ocean side) including Tohoku region.

6 During heavy snow year, we can see widely spreader heavy economical damage areas  
7 (potential road damage of over 50 million yen). The distributed roads in mountain range

8 skirt of Chugoku (Shimane Prefecture, Tottori Prefecture and Yamaguchi Prefecture)  
9 (marked as (g) in Fig 11) have also moved to heavy economical damage group. In addition

10 there is wide area for potential road damage of over 10 million yen damage in Hokkaido.  
11 This concludes that the economic damage changes remarkably between light snow conditions

12 to heavy snow condition. Therefore, these developed landslide hazard probability maps and  
13 economical damage maps will assist authorities, policy makers and decision makers, who are

14 responsible for infrastructural planning and development. These maps will assist them to  
15 identify the areas vulnerable for different scale snowfall events, and estimate the probable

16 economic damages. These results will guide them to allocate the funds for mitigation of  
17 potential economic damages and to arrange necessary adaptations to decrease landslide

18 damages through proper preparation.

19

20

## 21 **Conclusions**

22 Japan has one of the heaviest snowfalls in the world and uses snow water as the main water  
23 resources. Snowfall contributes substantially to water resources, but heavy snowfall can

24 result in severe damages to infrastructure and cause snowmelt induced landslides. Landslide  
25 hazards due to snowmelt are a common natural hazard in Japan. To evaluate the frequency

1 and distribution of snowmelt induced landslides hazards over Japan, this study uses a  
2 probabilistic model based on multiple logistic regression analysis, with particular reference to  
3 physical parameters such as hydraulic parameters (hydraulic gradient), geographical  
4 parameters (relief energy) and the four geological parameters (colluviums, paleogene  
5 sedimentary rock, new tertiary sedimentary rock, and granite) which are considered to be  
6 influential in the occurrence of landslides. All these physical data are obtained in digital  
7 format and the results of landslide hazard probability maps are portrayed in 1km×1km  
8 resolution digital maps. Hydraulic gradient is the hydraulic parameter, which includes the  
9 effect of snowmelt. To estimate snowmelt and associated infiltration in light, average and  
10 heavy snow years, a widely used Snow Water Equivalent model (SWE) is used. Using the  
11 constructed spatial data-sets, a multiple logistic regression model is applied and landslide  
12 susceptibility maps are produced showing the spatial-temporal distribution of landslide  
13 hazard probabilities over Japan using 1km×1km resolution grid cells.

14 The results show that the highest landslide hazard probability exists in the mountain ranges  
15 on the western side of Japan (Japan Sea side). The developed landslide hazard probability  
16 maps clearly separate the high risk and low risk areas using 95% probability threshold.  
17 According to the snowmelt amount in light, average and heavy snow years, following regions  
18 are identified having over 95% landslide hazard probability;

19 Light snow year- Hokuriku region

20 Average snow year- Hokuriku region and Tohoku region

21 Heavy snow year- West side of Japan (Japan Sea side)

22 The developed landslide hazard probability map is then verified using the past landslide  
23 events in Aizu region in Fukushima prefecture, located in a landslide prone region.  
24 Verification proved that, areas identified as high risk areas (having over 90% landslide  
25 hazard probability in numerical modeling), show 87% agreement with observed landslides in

1 the Aizu region. In addition, the relationship between landslide hazard risk and weather  
2 factors, and the economical damage due to landslides are discussed in this paper. The  
3 developed landslide hazard probability maps and economical damage maps will assist  
4 authorities, policy makers and decision makers, who are responsible for infrastructural  
5 planning and development, as they can identify landslide-susceptible areas and thus decrease  
6 landslide damage through proper preparation.

7

### 8 **Acknowledgement**

9 This research was funded by Global Environment Research Fund (GERF-S-4) of the  
10 Ministry of the Environment of Japan and Grant-in-Aid for Scientific Research from  
11 Japanese Society for Promotion of Science (JSPS) (Representative: Prof. Norihiro Izumi).  
12 Authors would like to thank for their generous financial assistances.

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## **Figure Captions**

Fig 1. Schematic diagram for infiltration analysis to obtain the hydraulic gradient

Fig 2. Observed landslide locations in Aizu region

Fig 3 Distribution of daily average SWE

Fig 4 Distribution of snowmelt in light, average and heavy snow years

Fig 5 Developed logistic curves for four geological properties

Fig 6 Snowmelt induced landslide hazard probability

Fig 7 Model verification with observed landslides

Fig 8 Municipal areas identified as heavy disastrous areas

Fig 9 Number of landslides recorded during snow-melting season in each year

Fig 10 Relationship between snow depths versus weather condition

Fig 11 Developed economical damage distribution maps