Assessment of snowmelt triggered landslide hazard and risk in Japan

*Saeki Kawagoe, So Kazama , and Priyantha Ranjan Sarukkalige**

Saeki Kawagoe

Graduate school of Environmental studies, Tohoku University, 6-6-20, Aramaki aza aoba, Aoba ku, Sendai, 981-8579, Japan

Email: kawagoe@kaigan.civil.tohoku.ac.jp

So Kazama

Graduate school of Environmental studies, Tohoku University, 6-6-20, Aramaki aza aoba, Aoba ku, Sendai, 981-8579, Japan

Email: kazama@kaigan.civil.tohoku.ac.jp

Priyantha Ranjan Sarukkalige*

Department of Civil Engineering, Curtin University of Technology, GPO Box U1987, Perth, WA 6845, Australia

Email: P.Sarukkalige@curtin.edu.au

***Corresponding Author**

Priyantha Ranjan Sarukkalige
Department of Civil Engineering,
Curtin University of Technology,
GPO Box U1987,
Perth, WA 6845,
Australia

Tel: +61-8-9266-3530
Fax: +61-8-9266-2681
Email: P.Sarukkalige@curtin.edu.au

Abstract

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

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

1. Introduction

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

There is much research on landslide hazard evaluation; in particular, Guzzetti *et al*. (1999) have summarized many cases of landslide hazard evaluation studies. In the literature there have been numerous studies involving landslide hazard evaluation and they concerned different causes and used different approaches; Geological hazards triggered by earthquake shaking, rainstorm, rapid snowmelt and human activity (Han et al, 2007). Only few research available on snowmelt induced landslide hazard assessments (Guzzetti et al, 2002; Gokceoglu et al, 2005; Naudet et al, 2008). Shortage of snowfall observation stations and difficulty in developing spatial distribution of snowmelt induced landslides may lead to lack of research studies. The Japanese meteorological agency attempts to quantify snowfall over a wide area with one observation point at every 400 km2, referred to as Auto Meteorological Acquisition Data System (AMeDAS). However, no observation points are located in the high elevation regions which suffer the heaviest snowfalls. Remote sensing is an effective tool that can be used to estimate the size of snow-covered areas and to make detailed estimates of the amount of snowfall (Koike *et al*., 1985; Kazama and Sawamoto, 1995; Derksen *et al*., 2000). Numerous studies have shown that remote sensing tools are capable of determining snow depth and snow amount in localized areas (Tait, 1998; Koenig and Forster, 2004; Dong, *et al*., 2005). Also, numerical simulations can express temporal variations in the snow depth and snow amount (Yamazaki *et al*., 1999; Inoue and Yokuyama, 2003).

In the literature there have been numerous studies involving landslide hazard evaluation and they used different assessing approaches; deterministic and statistical approaches. Wu and Sidle, 1995; Gokceoglu and Aksoy, 1996; Atkinson and Massari, 1998; Yilmazer et al, 2003; Xie et al, 2007 presented some deterministic approaches using geotechnical methods, whereas, Temesgen *et al,* (2001); Lee and Min (2001); Ohlmacher and Davis (2003); Westen *et al*., (2003) used statistical approaches. Also some studies compared the assessments from statistical approaches and deterministic approaches and discussed their advantages and disadvantages (Calcaterra *et al* 1998; Aleotti and Chowdhury, 1999; Lee *et al,* 2008). Deterministic approaches are based on slope stability analyses, and are only applicable when the ground conditions are fairly uniform across the study area and the landslide types are known and relatively easy to analyse (Dai et al., 2001). Statistical approaches on the other hand are indirect hazard mapping methodologies that involve statistical determination of the combinations of variables that have led to landslide occurrence in the past. Probability is the key issue in the statistical analysis. Also, the probabilistic method is suitable and can be used over a large area where numerous natural slopes exist (Refice and Capolongo (2002); Guzzetti *et al*, (2005); Zolfaghari and Heath, (2008); Shou et al (2008). Thus, the use of probabilistic methods has become an important aspect in assessing landslide hazard maps where the probability, location, and frequency of future landslide can be predicted. It provides potential to assess the landslide hazard in a given area in terms of probability of occurrence of a potentially damaging landslide event within a specified period using probabilistically. In this study, a probabilistic analysis approach is implemented in order that we can evaluate the landslide hazard probability due to snowmelt over whole of Japan, with consideration of snowmelt as main external parameter. Therefore, this assessment will be a vital subject for authorities, as they can assess and predict landslide-susceptible areas and thus decrease landslide damage through proper preparation, and it assists decision makers who are responsible for infrastructural development and environmental protection.

2. Methods and Materials

Many researchers have tried to understand the factors affecting landslide hazards. Geographical and geological factors had been considered using aerial photographs, and remote sensing data (Kojima *et al*., 2003; Tarolli and Tarboton, 2006). However, hydrology conditions, especially rainfall and snowmelt condition should be considered with landslide hazard evaluations (Richard *et al*, 1996; Jochen *et al.*, 2004; Temsgen, et al, 2001).

In this study, several factors affecting landslide hazards are taken into account and categorized into groups; hydraulic factors, geological factors and geographical factors. Change in hydraulic gradient due to snowmelt is considered as hydraulic factors. To estimate the snowmelt and associated infiltration, the Snow Water Equivalent (hereafter referred to as SWE) model developed by Kazama et al (2008) is used in this study. It produces the amount of snowmelt which used as the input for infiltration analysis to estimate hydraulic gradient. The relief energy, slope gradient and topography are considered as the geographical factors. Four commonly available geological types in Japan; colluviums, paleogene sedimentary rock, new tertiary sedimentary rock, and granite represent the geological factors. All these data are obtained in digital format and data resolution is 1km×1km. Therefore, the results of landslide hazard probability are portrayed in a 1km×1km resolution map. Taking landslide induced damages to infrastructure in landslide prone areas into account, an economic damage assessment is conducted. Finally, the landslide hazard probabilities (hazard index) are combined with economic damage evaluations (economic index) to develop the landslide hazard risk assessment.

2.1 Hydraulic factors

Hydraulic gradient is an active property in initiation of landslides. Increase of hydraulic gradient cause piping phenomenon and sediment flow on a slope (Moriwaki et al, 2006; Sultan, et al, 2007). Change in hydraulic gradient as a result of infiltration of snowmelt water is used as the main parameter to reflect the hydraulic condition in this study. The hydraulic gradient ($\Delta h / L$) is derived from the phreatic line obtained by unsaturated infiltration analysis based on Richards equation (Richards, 1931; Ross, 1990), using soil data, slope angle and snowmelt (snow water equivalent) as the main input data as shown in Fig 1. Two numerical models are used to evaluate hydraulic gradient. The SWE model is used to estimate snowmelt and an infiltration analysis is used to estimate the hydraulic gradient.

2.1.1 Snowmelt estimation

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

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

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

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

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

$$SM = K \times T \quad (2)$$

where K is the degree-day parameter (mm/ ^{0}C /day) and T is the mean daily temperature (^{0}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 results are converted to 1km×1km resolution to input to infiltration model. The estimated snowmelts are used as the main hydraulic input for the infiltration analysis.

2.1.2 Infiltration analysis

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

First the water volume content θ can be estimated as

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

Where θ is the water volume content, t is time step, *Vx* is the velocity in horizontal direction, and *Vz* is t the velocity in vertical direction.

The flow velocities (*Vx* and *Vz)* is obtained by of Darcy’s equation (Eq. 2).

$$V_x = -K_x \frac{\partial h}{\partial x}$$
$$V_z = -K_z \frac{\partial h}{\partial z} \tag{4}$$

Where *h* is the total hydraulic head, *Kx* is the unsaturated hydraulic conductivity in horizontal direction and *Kz* is the unsaturated hydraulic conductivity in vertical direction.

The total hydraulic head h is the sum of the hydraulic pressure head ψ and elevation head. The elevation head can be estimated using horizontal and vertical length components (*Lx* and *Lz*,) as $-L_x \sin\alpha - L_z \cos\alpha$

Therefore total head is

$$h = \psi - L_x \sin\alpha - L_z \cos\alpha \tag{5}$$

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

$$C\frac{\partial\psi}{\partial t} = \frac{\partial}{\partial x}\left(K_x \frac{\partial\phi}{\partial x}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial\phi}{\partial z}\right)$$

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

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

To solve this equation, two relationships have been used.

1) Relationship between unsaturated hydraulic conductivity *K* and water volume content *θ*

$$K_x = Ks_x\left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^{\beta}$$
$$K_z = Ks_z\left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^{\beta} \tag{7}$$

Where β is soil characteristic value

2) Relationship between pressure head ψ and water volume content *θ* (Bruseart 1968).

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

Where θs is the saturation water volume content, θr *is the* residual water volume content and Ks is the instauration hydraulic conductivity. These parameters can be obtained from the literature (Kawakami 2003). Four soil types (gravel, sand, silt and clay) are taken into account for the infiltration analysis and Table 1 shows the properties of each soil type.

Combining equation (4), equation (5) and equation (6), an iteration process is employed to solve these equations where ψ_0 is initial condition and ψ' is the saturation condition in each iteration step. The convergent value of hydraulic head is used to estimate the hydraulic gradient as $\Delta h / L$

2.2 Geographical factors

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

2.3 Geological factors

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

2.4 Historical landslide observations

A key assumption using this approach is that the potential (occurrence possibility) of landslides will be comparable to the actual frequency of landslides. Historical landslide hazard data for Aizu region in Fukushima prefecture, where lot of landslide damages are occurred in snow melting season in 2000, are used to compare the developed landslide hazard maps and actual landslides. From 21st March to 28th March, 2000, 61 landslides were occurred due to the snowmelt in Aizu region (over 5420.69 km2 area). This is the maximum number of landslides in recent history. These data were obtained from Kitakata and Wakamatsu Construction Office authority in Fukushima prefecture and converted to vector-type spatial landslide hazard map of 1km×1km resolution using the ARC/INFO GIS software (Sediment control division, 2001) of Fukushima prefecture). Fig 2 shows the observed landslide locations in Aizu region.

2.5 Economic damage data

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

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

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

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

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

3.1 Spatial distribution of snowmelt

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

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)

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

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

Where *P* is the probability of landslide occurrence, *σ0* is the interception, *σh* is the coefficient of hydraulic gradient, σ*r* is the coefficient of relief energy, *hydYn* is the hydraulic gradient, and *riliefYr* is the relief energy.

The results of the multiple logistic regressions expressing the relationships among hydraulic gradient and relief energy for each geological property are summarized in Table 3.

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

5. Results and discussions

The results of the probability model, the spatial distribution of landslide hazard probability based on snowmelt induced infiltration condition, geographical conditions and geological conditions of the area are portrayed on landslide hazard probability maps using Geographic Information System (GIS) technology. To evaluate the temporal changes, the probability is estimated for changing hydraulic factors using three identified snow conditions; heavy snow, average snow and light snow years.

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

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

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

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

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

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

Light snow year- Hokuriku region

Average snow year- Hokuriku region and Tohoku region

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

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

5.1 Model verification with past events

In many landslide susceptibility and hazard mappings, independent validation of statistical models for landslide hazard or susceptibility assessment is lacking (Remondo et al, 2003; Westen et al., 2003). In prediction modelling, the most important and the absolutely essential component are to carry out a validation of the prediction results (Chung and Fabbri, 2003). One of the objectives of the present study is to perform such validation using recorded past landslide data.

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

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

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

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.

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

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

5.4. Assessment of economical damages

The economic damage is assessed taking road damages owing to landslide into account. Three main factors are considered to estimate the economic damage by road damages due to landslides;

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

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

$$Total\,Cost = (T_C + L_c + \sum L \times M_R) \times \mathrm{Pr}\,obability \qquad (10)$$

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

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

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

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

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

Repairing cost (M_R) is obtained from the Ministry of Land infrastructure and Transport (Cost convenience analysis manual of the civil construction, 2003). This manual gives the repair cost for expressway and national road is 103,000 yen/m, and the repair cost for public highways is 77,000 yen/m. Also this manual gives the unit cost of time loss in monetary unit (T_i) as 519.6 yen/hour per vehicle (8.66 yen/min.vehicle) and travel cost per unit distance in monetary unit (L_i) as 6.24 yen/m. per vehicle. In addition the traffic data (average number of vehicles per day) published in traffic investigation result of Japan, by the Ministry of Land infrastructure and Transport (Traffic census, 2004), is used to estimate the average number of vehicles use the respective road.

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

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

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

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

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

d) Distributed road in Aizu region (Fukushima Prefecture)

e) Distributed road in Dewa mountain range (Akita Prefecture)

f) Distributed road in mountain range of Kiso and Ina (Gifu Prefecture)

In addition the areas having potential road damage of over 50 million yen expands towards west coast (Japan Sea side) and east coast (Pacific Ocean side) including Tohoku region. During heavy snow year, we can see widely spreader heavy economical damage areas (potential road damage of over 50 million yen). The distributed roads in mountain range skirt of Chugoku (Shimane Prefecture, Tottori Prefecture and Yamaguchi Prefecture) (marked as (g) in Fig 11) have also moved to heavy economical damage group. In addition there is wide area for potential road damage of over 10 million yen damage in Hokkaido. This concludes that the economic damage changes remarkably between light snow conditions to heavy snow condition. Therefore, these developed landslide hazard probability maps and economical damage maps will assist authorities, policy makers and decision makers, who are responsible for infrastructural planning and development. These maps will assist them to identify the areas vulnerable for different scale snowfall events, and estimate the probable economic damages. These results will guide them to allocate the funds for mitigation of potential economic damages and to arrange necessary adaptations to decrease landslide damages through proper preparation.

Conclusions

Japan has one of the heaviest snowfalls in the world and uses snow water as the main water resources. Snowfall contributes substantially to water resources, but heavy snowfall can result in severe damages to infrastructure and cause snowmelt induced landslides. Landslide hazards due to snowmelt are a common natural hazard in Japan. To evaluate the frequency and distribution of snowmelt induced landslides hazards over Japan, this study uses a probabilistic model based on multiple logistic regression analysis, with particular reference to physical parameters such as hydraulic parameters (hydraulic gradient), geographical parameters (relief energy) and the four geological parameters (colluviums, paleogene sedimentary rock, new tertiary sedimentary rock, and granite) which are considered to be influential in the occurrence of landslides. All these physical data are obtained in digital format and the results of landslide hazard probability maps are portrayed in 1km×1km resolution digital maps. Hydraulic gradient is the hydraulic parameter, which includes the effect of snowmelt. To estimate snowmelt and associated infiltration in light, average and heavy snow years, a widely used Snow Water Equivalent model (SWE) is used. Using the constructed spatial data-sets, a multiple logistic regression model is applied and landslide susceptibility maps are produced showing the spatial-temporal distribution of landslide hazard probabilities over Japan using 1km×1km resolution grid cells.

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

Light snow year- Hokuriku region

Average snow year- Hokuriku region and Tohoku region

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

The developed landslide hazard probability map is then verified using the past landslide events in Aizu region in Fukushima prefecture, located in a landslide prone region. Verification proved that, areas identified as high risk areas (having over 90% landslide hazard probability in numerical modeling), show 87% agreement with observed landslides in the Aizu region. In addition, the relationship between landslide hazard risk and weather factors, and the economical damage due to landslides are discussed in this paper. The developed landslide hazard probability maps and economical damage maps will assist authorities, policy makers and decision makers, who are responsible for infrastructural planning and development, as they can identify landslide-susceptible areas and thus decrease landslide damage through proper preparation.

Acknowledgement

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

References

Ahuja, L.R., Naney, J.W, and Williams R.D., 1985. Estimating soil-water characteristics from soimpler properties or limited data, Soil science society of America Journal, 49: 1100-1105

Akazawa, Y., Numaguchi, A., Emori, S., 2005. Regional characteristics of the change in snow amount in the course of the global warming –comparison between model and observational data-, Journal of Japan Society of Hydrology and Water, 18: 510-520 (In Japanese, with English abstract)

Aleotti P., and Chowdhury, R., 1999, Landslide hazard assessment: summary review and new perspectives, Bulletin of Engineering Geology and Environment 58: 21–44

Aoyama, K., Nakamata, S., Ogawa, S., 1984, Consideration on the Relations between Landslide and Snow in Niigata Prefecture, Landslides - Journal of Japan Landslide Society, 21, 3: 11-16 (In Japanese, with English abstract)

Atkinson P.M., and Massari, R., 1998, Generalized linear modelling of landslide susceptibility in the central Apennines, Italy, Computers & Geosciences 24: 373–385

Ayalew, L., Yamagishi, H., Marui, H. and Kanno, T., 2005. Landslides in Sado Island of Japan: Part I. Case studies, monitoring techniques and environmental considerations, Engineering Geology, 81, 4: 419-431,

Ayalew, L., Yamagishi, H., Marui, H. and Kanno, T., 2005. Landslides in Sado Island of Japan: Part II. GIS-based susceptibility mapping with comparisons of results from two methods and verifications, Engineering Geology, 81, 4: 432-445

Bruseart, W.F., 1968, The permeability of a porous medium determined from certain probability laws for pore size distribution. Water resources research, 4: 425-434.

Calcaterra, D., Gili, J.A., Iovinelli, R., 1998, Shallow landslides in deeply weathered slates of the Sierra de Collcerola (Catalonian Coastal Range, Spain), Engineering Geology, 50: 283-298

Chung, C. J. F., and Fabbri, A.G., 2003, Validation of spatial prediction models for landslide hazard mapping. Natural Hazards 30: 451–472

Cost Convenience Analysis Manual of the Civil Construction, (2003), Ministry of Land, Infrastructure and Transport, p172 (In Japanese)

Crescenzo, G, D., and Santo, A, 2005, Debris slides–rapid earth flows in the carbonate massifs of the Campania region (Southern Italy): morphological and morphometric data for evaluating triggering susceptibility , Geomorphology, 66,: 255-66.

Dai, F.C., Lee, C.F., Li, J., Xu, Z.W., 2001, Assessment of landslide susceptibility on the natural terrain of Lantau Island, Hong Kong, Environmental Geology 40: 381–391

Derbyshire, E, Van, T, Billard, A and Meng, X, 1995, modeling the erosion susceptibility of landslide catchments in thick loess: Chinese variations on a theme by Jan de Ploey, CATENA, 25: 315-331

Derksen, C., LeDrew, E., Goodison, B., 2000, Temporal and spatial variability of North American prairie snow cover (1988–1995) inferred from passive microwave-derived snow water equivalent imagery, Water Resources Research 36: 255–266.

Disaster report 2004, 2005, Ministry of land Infrastructure and Transport Japan, pp20 (In Japanese)

Dong, J., Walker, J.P., and Houser, P.R., 2005, Factors affecting remotely sensed snow water equivalent uncertainty, Remote Sensing of Environment 97: 68-82

Gokceoglu, C., and Aksoy, H., 1996, Landslide susceptibility mapping of the slopes in the residual soils of the Mengen region (Turkey) by deterministic stability analyses and image processing techniques, Engineering Geology 44: 147–161

Gokceoglu, C., Sonmez, H., Nefeslioglu, H.A., Duman, T.Y., Can, T., 2005. Kuzulu landslide (Sivas, Turkey) and landslide-susceptibility map of its near vicinity, Engineering Geology, 81, 1: 65-83

Gosh, R.K., 1980, Estimation of soil moisture characteristics from mechanical properties of soils, Soil science Journal, 130, 2: 60-63

Guzzetti, F., Bruce, D., Malamud, L. Reichenbach, P., 2002. Power-law correlations of landslide areas in central Italy, Earth and Planetary Science Letters, 195: 169-183

Guzzetti, F., Carrara, A., Cardinali, M., Reichenbach, P., 1999, Landslide hazard evaluation: a review of current techniques and their application in a multi-scale study, Central Italy Geomorphology, 31:181-216

Guzzetti, F., Reichenbach, P., Cardinali, M., Galli, M., Ardizzone, F., 2005, Probabilistic landslide hazard assessment at the basin scale, Geomorphology, 72: 272-299

Guzzetti, F., Reichenbach, P., Cardinali, M., Galli, M., Ardizzone, F., 2005, Probabilistic landslide hazard assessment at the basin scale, Geomorphology, 72: 272-299

Hair, J.F., Anderson, R.E., Tatham, R.L., Black, W.C., 1998, Multivariate data analysis. 5th eddition, Prentice-Hall, London.

Han, J., Wu, S., Wang, H., 2007, Preliminary Study on Geological Hazard Chains Earth Science Frontiers, 14, 6: 11-20

Inoue S., and Yokoyama K. 2003, Estimates of snowfall depth, maximum snow depth, and snow pack conditions in Japan by using five global warming predicted data, Journal of Agricultural Meteorology 59: 227-236

Inoue, S., Kawashima, S., Takahashi, Y., 2002. Estimating the beginning day of Japanese cedar pollen release under global climate change, Global Change Biology, 8, 1165-1168

Jochen, S., and Richard, D., 2004, Modeling historical climate variability and slope stability, Geomorphology, 60: 433-447,

Kawakami, F., 2003. Soil Mechanics, Morikita publications, Tokyo, pp 276 (in Japanese)

Kazama, S., and Sawamoto, M., 1995, Estimation of the snow depth distribution and snow water resources in wide area, Int. Conf. on Water Resources & Environment Research, Towards the 21st Century, 659-666

Kazama, S., and Sawamoto, M., 1995. Estimation of the snow depth distribution and snow water resources in wide area, Int. Conf. on Water Resour. & Environment Resear. Towards the 21st Century, 1: 659-666

Kazama, S., Izumi, H., Sarukkalige, P.R., Nasu, T., Sawamoto. M., Estimating snow distribution over a large area and its application for water resources, Hydrological Processes, 22, 13: 2315-2324

Koenig, L., S., and Forster, R., R., 2004, Evaluation of passive microwave snow water equivalent algorithms in the depth hoar-dominated snowpack of the Kuparuk River Watershed, Alaska, USA, Remote Sensing of the Environment 93: 511-527.

Koike, T., Takahasi, Y. and Yosino, S., 1985, Estimation of basin-wide snow water equivalent using snow-covered area, Modeling Snowmelt-Induced Processes 155:193-202 (In Japanese, with English abstract).

Kojima, H., Oobayashi, S., Kitamura, R., 2003, An application of satellite thermal infrared data in triggered - factor inverse estimation for identifying hazardous-slope composed of construction management and engineering, JSCE, 749: 99-110 (In Japanese, with English abstract)

Landslide Economic Damage Evaluation Manual, 2003, Ministry of Land, Infrastructure and Transport, Japan, p184 (In Japanese)

Lee, C. T., Huang, C.C., Lee, J. F., Pan, K. L., Lin, M. l., Dong, J. J., 2008, Statistical approach to earthquake-induced landslide susceptibility, Engineering Geology, 100: 43-58

Lee, S., and Min, K., 2001, Statistical analysis of landslide susceptibility at Yongin, Korea, Environmental Geology 40: 1095–1113

Maruyama, K., Kondou M ., 1988. Landslides in Niigata Prefecture in Snow Season, Journal of Japan Landslide Society, 25,2: 18-26 (In Japanese, with English abstract)

Maruyama, K., Takeshi, S., 2004. Simply presumption equation of daily snow melt infiltration to ground level for snowfall regional landslide mitigation, Journal of Japan Landslide Society, 41,4: 85-90 (In Japanese, with English abstract)

Matsuura, S., Asano, S., Okawamoto, T. and Takeuchi, T., 2003. Characteristics of the displacement of a landslide with shallow sliding surface in a heavy snow district of Japan, Engineering Geology, 69:15-35.

Ministry of Land, Infrastructure and Transport, 2007. landslides due to snowmelt, (http://www.mlit.go.jp/river/sabo/saigai_info/050513/050513.pdf)

Moriwaki, H., Yazaki, S., Huang, W., (2006), Simulation Analysis of rainfall induced groundwater flow in association with slope failure, Journal of Japan landslide society, 43,1: 9-19 (In Japanese, with English abstract)

National-land information data, 2001, Ministry of Land, Infrastructure, Transport and Tourism, http://nlftp.mlit.go.jp/ksj/old/cgi-bin/_kategori_view.cgi

Naudet, V., Lazzari, M., Perrone, A., Loperte, A., Piscitelli, S., Lapenna V., 2008. Integrated geophysical and geomorphological approach to investigate the snowmelt-triggered landslide of Bosco Piccolo village (Basilicata, southern Italy), Engineering Geology, 98,3-4: 156-167

Niwa, K. and Moritani, A., 1990, Model of snowmelt runoff for prediction of dam inflow, Institute of Construction Ministry Report 2826, 121-129 (In Japanese, with English abstract)

Ogawa, S., Kamei, T., Wada, T., Hashimoto, M., 1986. The variation characteristics in the groundwater level, pore water pressure and underground temperature during snow-melting season in landslide areas, Landslides- Journal of Japan Landslide Society, 23, 3: 21-27 (In Japanese, with English abstract)

Ohlmacher,G.,C., and Davis, J.T., 2003, Using multiple logistic regression and GIS technology to predict landslide hazard in North Kansas, Engineering Geology, 69: 331-343

Refice, A., and Capolongo, D., 2002, Probabilistic modeling of uncertainties in earthquake-induced landslide hazard assessment, Computers & Geosciences, 28 : 735-749

Remondo, J., González, A., Ramón, J., Cendrero, A., Fabbri, A., Chung, C. J. F., 2003, Validation of landslide susceptibility maps: examples and applications from a case study in Northern Spain. Natural Hazards 30: 437–449

Report on statistical water damage: 2000-2005, 2007, Publication of Ministry of Land, Infrastructure and Transport (In Japanese).

Richard, D., Angelo, C and Stefan, J., 1996, Databases and GIS for landslide research in Europe, Geomorphology, 15: 227-239.

Richards, L. A., 1931, Capillary Conduction of Liquids Through Porous Mediums, Journal of Applied Physics, 1: 318-333

Rikiishi, K., 2006, Review of satellite observations of the cryosphere with special reference to the recent decline of the seasonal snow cover in the Northern Hemisphere., Journal of Japanese Society of Snow and Ice, 68: 581-587 (In Japanese, with English abstract)

Ross, P. J., 1990, Efficient Numerical Methods for Infiltration Using Richards' Equation Water Resources Research, 26: 279-290

Sato, A., 2006. Heavy snowfall disaster in the winter of 2005-2006, Journal of Japan Natural Disaster Science, 25:71-81 (In Japanese, with English abstract)

Sediment control division report, 2001, Landslide report on Aizu region, Katakana and Wakamatsu Construction Office in Fukushima prefecture (In Japanese)

Shou, K., Chen, Y., Liu, H., 2008, Hazard analysis of Li-shan landslide in Taiwan, Geomorphology (in press)

Sultan, N., Voisset, M., Marsset, B., Marsset, T., Cauquil, E., Colliat, J.L., 2007, Potential role of compressional structures in generating submarine slope failures in the Niger Delta, Marine Geology, 237: 169-190

Tait, A.B., 1998, Estimation of snow water equivalent using passive microwave radiation data, Remote Sensing of the Environment 64: 286–291.

Tarolli, P., and Tarboton, G., 2006, A new method for determination of most likely landslide initial points and the evaluation of digital terrain model scale in terrain stability mapping, Hydrology and Earth system sciences, 10: 663-677.

Temesgen, B., Mohammed, M. U., Korme, T., 2001, Natural hazard assessment using GIS and remote sensing methods, with particular reference to the landslides in the Wondogenet

Area, Ethiopia Physics and Chemistry of the Earth, Part C: Solar, Terrestrial & Planetary Science, 26: 665-675

Temsgen, B., Mohammed, M, U. and Korme, T., 2001, Natural hazard assessment using GIS and Remote sending methods, with particular reference to the landslides in the Wondogenet area, Ethiopia, Physics and Chemistry of east part, 26-9: 665-675.

Traffic census, 2004. Published by the Ministry of Land, Infrastructure and Transport. (http://www.mlit.go.jp/road/ir/ir-data/ir-data.html)

Westen C.J., Rengers N., Soeters R., 2003, Use of geomorphological information in indirect landslide susceptibility assessment. Natural Hazards 30: 399–419

Wu, W., Sidle, R.C., 1995, A distributed slope stability model for steep forested basins, Water Resource Research 31: 2097–2110.

Xie, M., Tetsuro, E., Qiu, C., Jia, L., 2007, spatial three-dimensional landslide susceptibility mapping tool and its applications, Earth Science Frontiers, 14: 73-84

Yamazaki, T., Sakuraoka, T., Nakamura T. and Kondo, J., 1999, A one-dimensional model of the evolution of snow-cover characteristics, Annals of Glaciology 18: 22-26

Yilmazer, I, Yilmazer, O., Saraç, C., 2003, Case history of controlling a major landslide at Karandu, Turkey, Engineering Geology, 70: 47-53

Zolfaghari, A., and Heath A.,C., 2008, A GIS application for assessing landslide hazard over a large area, Computers and Geotechnics, 35: 278-285

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