A method for delineating restricted hazard areas due to debris flows

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ABSTRACT: To prevent debris-flow disasters in Japan, structural and non-structural measures for debris-flow disasters have been promoted efficiently. In April, 2001, Japan enacted a Sediment-Related Disaster Prevention Law to protect lives and bodies from landslides and debris flows. The purpose of the law is to promote measures for preventing sediment-related disasters, arrange warning and evacuation systems in hazardous areas, and regulate specific types of development within areas likely to be susceptible to landslides and debris flows. At the end of 2006, around 9300 restricted areas at risk from debris flows were designated under the law. In this report, we state the idea of delineating hazardous areas through verification of past debris-flow events. We propose methods of identifying areas subject to debris-flow inundation and areas debris flow will not reach. Using our methods, we identify areas where warning and evacuation systems should be established. We also identify areas where development should be restricted by considering the range of forces likely to be exerted on buildings within the inundation zones and comparing those forces to the strengths of the affected buildings (wooden structure).

1 INTRODUCTION

In Japan 70% of the land consists of mountain ranges and hills, and in the remaining narrow livable space the population exceeds one hundred million inhabitants. Population concentrations in urban areas continue to increase, and many people reside in dangerous areas. According to the results of nationwide investigations in March 2003, the number of sediment-related hazard areas that are prone to the failure of land with steep slopes, debris flows or landslides is as many as 525,307. In 2006, sediment-related disasters occurred in both Kyushu and Honshu Districts where debris flows and slope failures hit a great number of houses and caused 24 fatalities.

Under the circumstances, the Japanese Government enforced in 2001 a law to promote soft countermeasures, such as the establishment of warning and evacuation systems (Sediment-related Disaster Prevention Law), to reduce loss of lives. In this law, Law (2001), dangerous land such as the foot of a cliff, the downstream basin of a torrent, and areas in landslide terrain can be designated as sediment-related hazard areas. Such designations enact establishment of warning and evacuation systems, and at the same time enable regulations that restrict building usage and limit development. Establishing such hazard zones requires accuracy and efficiency. It also requires identifying the fluid dynamic forces exerted by a debris flow on structures that are inundated and an estimation of the amount of sediment likely to be delivered. Such computations typically are complicated and require a lot of time and effort.

In this regard, we have been working on development and implementation of a hazard-zoning system whereby the process of identifying and delineating sediment-related hazard areas can be made accurately and efficiently, Takanashi et al. (2004). This system utilizes state-of-the-art GIS (Geographic Information System) technologies by means of three-dimensional topographic information and ortho-photos.

2 ADVANTAGES OF THE HAZARD-ZONING SYSTEM

2.1 *Increased efficiency and reduced cost*

As stated above, a huge amount of time and cost is required to identify sediment-related hazard areas. Hence, the hazard-zoning system we developed enabled the time for work to be shortened and the cost to be reduced, by increasing the efficiency of work and automating the complicated work that requires time and effort. At the same time it allows for the visualization of topographical and geological conditions to provide support for the judgment made by technical personnel.

2.2 *Improved objectivity, accuracy, and reproducibility*

Once sediment-related hazard areas have been specified, the law enacts regulations on structures and limitations on development. Therefore, it is important to accurately, objectively, and reproducibly designate such zones. Hence, upon identifying hazardous areas subject to restrictions, a mechanism has been devised by which the accuracy, objectivity, and reproducibility of such designations can be secured.

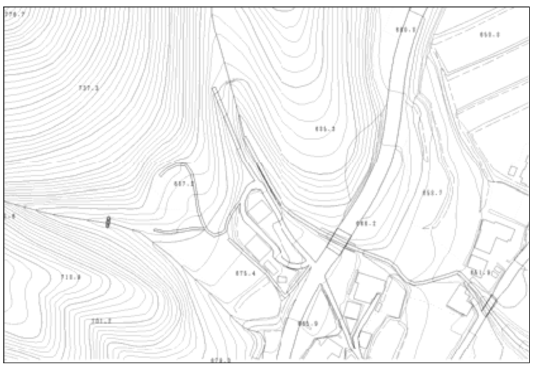
3 DEVELOPMENT OF A SYSTEM FOR DELINEATING DEBRIS-FLOW DISASTER HAZARD ZONES

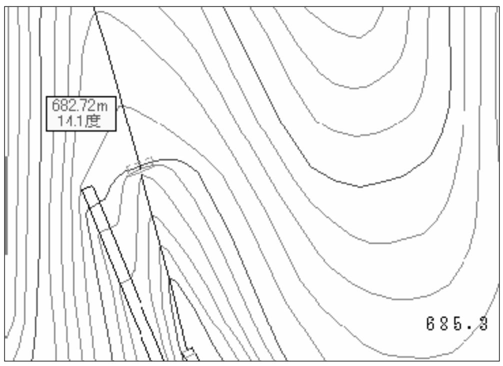
The system for establishing sediment-related hazard areas, etc. was developed in terms of three phenomena: failures of land with steep slopes, debris flows, and landslides. Of these phenomena, this paper discusses development of a method for delineating debris-flow hazard zones, a method that required the most complicated and high-grade technologies.

3.1 *Spatial information*

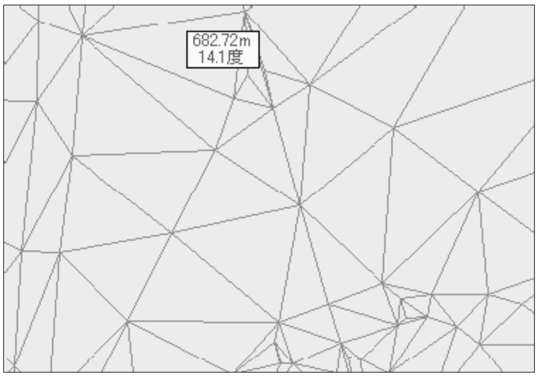
The following three types of spatial information are required for delineating hazard zones:

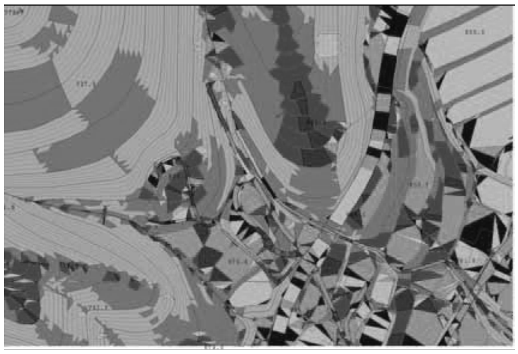
1) Digital maps.



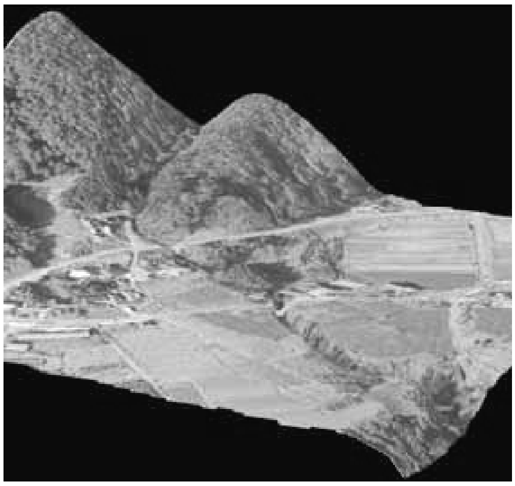


2) Three-dimensional topographical models. TIN (Triangulated Irregular Network) and DEMs (digital elevation models).





3) Orthophoto and three-dimensional view.



3.2 *Establishing the course of debris flow and the starting point of inundation*

The course of a debris flow is indicated on a screen by designating a point 200 m upstream of the starting point of inundation that is estimated on a map and in an ortho-photo, whereupon the system automatically searches the route of flow from a three-dimensional topographical model. By adopting this technique, the difference in the result of route setting according to the person who made the setting was eliminated, thus securing reproducibility. Regarding overflow in the bend of a channel, the system has been made to be able to handle it by incorporating a tool that enables the set watercourse to be corrected and changed.

Since the setting of the starting point of inundation needs to be determined by making comprehensive judgment based on the topographical situation of the whole basin as well as local conditions (such as houses and local topography), a function has been developed in which the setting of the starting point of inundation is made by displaying a longitudinal profile and plan of the flow course and designating a threshold gradient on the longitudinal profile. Fig. 1 shows a longitudinal profile of a stream course in which each gradient section is indicated by a different color. (In the figure, the vertical dotted line marked with 0 denotes the starting point of inundation.)

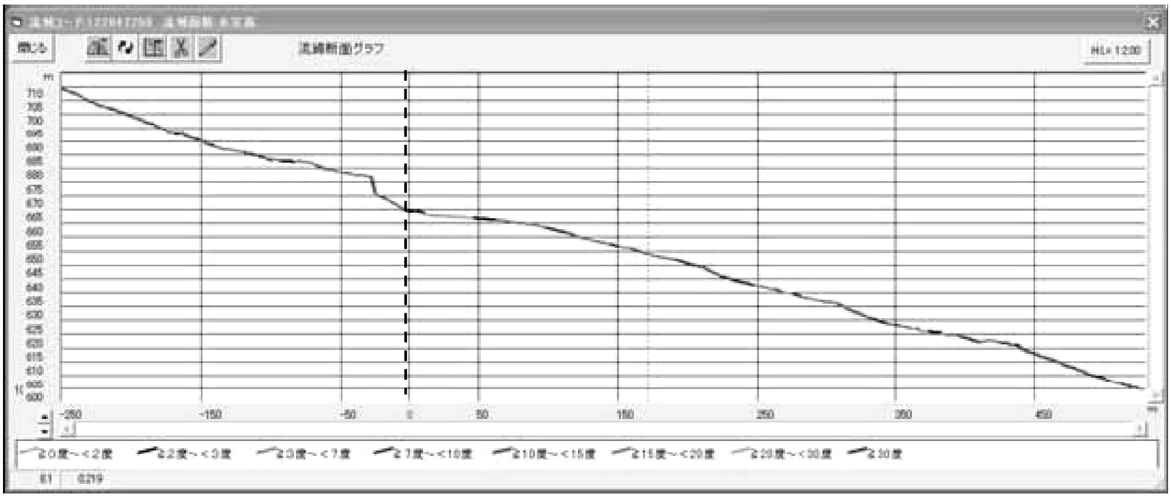


Figure 1. A longitudinal profile of a stream course .

3.3 *Designating hazard-zone limits*

A "zone with danger of harm" (Yellow Zone) means the land is recognized as posing a risk of causing harm to life and property in the event of a debris flow. Such a zone is defined as those areas downstream of the identified inundation starting point that have a gradient of 2° or more and a catchment area of 5 km^2 or less.

In this system, a mechanism has been made in which, as shown in Fig. 2, by designating the points on both sides of the channel having a relative cross-section height of 10 m above the inundation starting point, the zones of which gradient in the lower reach is 2° or more are automatically delineated. In the algorithm, the steepest gradient vector is drawn from the starting point of calculation toward the direction of a circle of 40 m (horizontal distance) in radius. Next, a 30° open angle vector is drawn, which is 30° open toward the outer angle from the starting point of this steepest gradient vector. If the difference in relative height between the ground height pointed by the steepest gradient vector and the ground height pointed by the 30° open angle vector is 5 m or more, the angle of the 30° open vector will be reduced so that the difference in relative height with the outer angle will become 5 m. This calculation is repeated until the gradient of the land with the steepest gradient vector becomes less than 2°. Note that the steepest gradient vector is basically drawn with the radius being set to 40 m, but it is possible to use a radius of 20 m or 60 m as well depending on the topography.

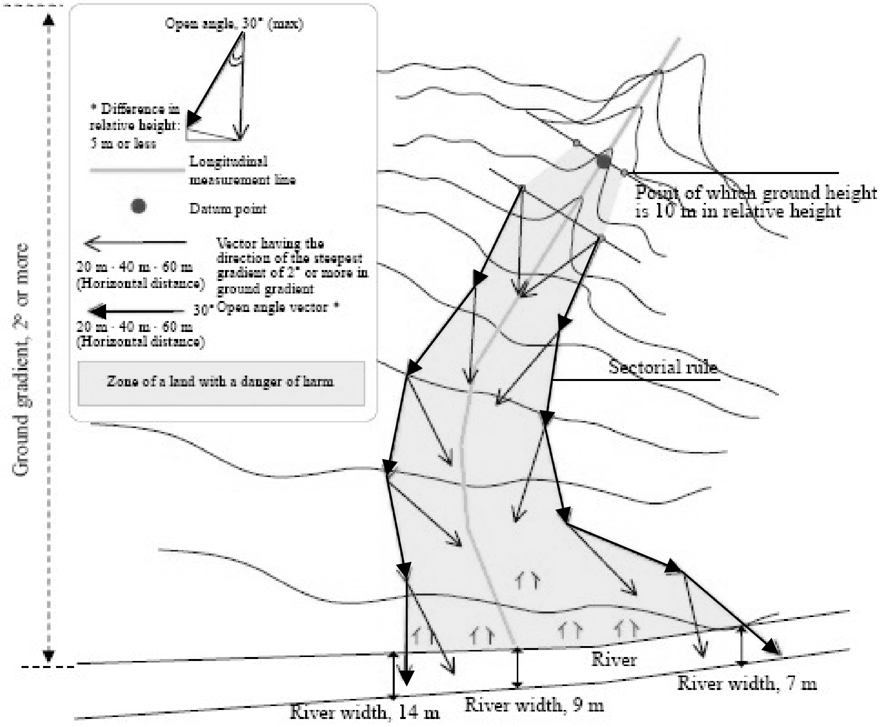


Figure 2. Method of setting a "land with danger of harm"

3.4 *Delineating a "zone with a considerable danger of harm "*

A "zone with a considerable danger of harm" (Red Zone) is a zone of land in which the magnitude of a force that is estimated to be applied to a building as a result of a debris flow surpasses the force that an ordinary building (wooden structure) can withstand without sustaining damage. In this zone there is a high probability for considerable loss of life. Steps for designating such a zone include:

1) Determining the cross-sectional shape and longitudinal gradient perpendicular to the flow direction of a debris flow. The measurement lines are set at 20 m intervals from the starting point of inundation to establish closely spaced channel-area cross sections (Fig. 3). The longitudinal gradient at each cross section represents the average gradient in a section 200 m upstream and downstream of the cross section.

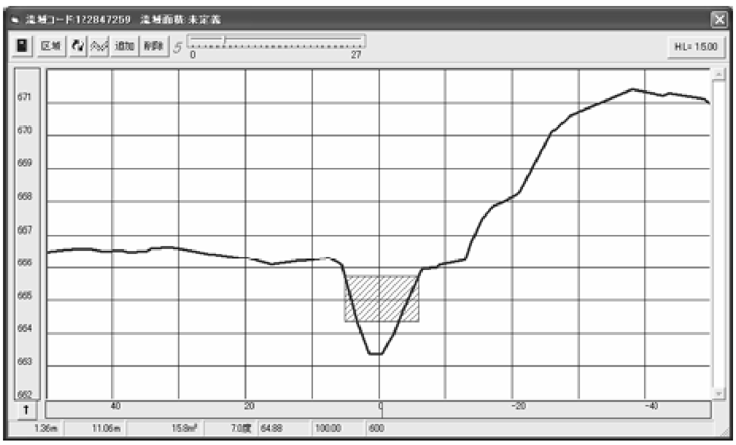


Figure 3. Cross-sectional view (of a part 100 m downstream of the starting point of inundation).

2) For each cross section, the peak flow rate of a debris flow is calculated by using Eq. 1. Eq. 1 is an expression of the relation between the volume sediment concentration of a debris flow and its peak flow rate, where Qsp_i is the peak flow rate at an arbitrary calculation point, Cd_i is the volume sediment concentration of the moving debris flow, θ_i is the channel gradient, Qsp_0 is the peak flow rate of the debris flow at the inundation starting point, Cd_0 is the volume sediment concentration of the moving debris flow at that point, V_0 is the sediment discharge, and C_* is the volume concentration of deposited debris.

$$Qsp_i = \frac{(C_* - Cd_0)}{(C_* - Cd_i)} Qsp_0 \ , \ Qsp_0 = \frac{0.01\, C_*}{Cd_0} V_0 \tag{1}$$

Computations of Cd_i and Cd_0 are given by Eq. 2. If the calculated values, Cd_i and Cd_0, are greater than $0.9C_*$, then they will be set to be $0.9C_*$, but the lower limit will not be set. However, if the gradient of the land at each calculation point forms an adverse slope ($\theta_i > \theta_{i-1}$), then Cd_i will be set to $Cd_i = Cd_{i-1}$ on condition that the amount of debris will not increase downstream.

$$Cd_i = \frac{\rho \tan\theta_i}{(\sigma - \rho)(\tan\varphi - \tan\theta_i)} \tag{2}$$

In Eq. 2, each of σ, ρ, φ, and θ represent the following parameters:

σ = density of pebbles contained in the debris flow, t/m^3; ρ = density of flowing water contained in the debris flow, t/m^3; φ=internal friction angle of debris, degrees; and θ=surface slope, degrees.

3) The width of the inundation zone is set by using Eq. 3, a type of Manning's formula, if the cross-section can be clearly delineated, or otherwise by using Eq. 4:

$$U_i = \frac{Q_i}{A_i} = \frac{1}{n} R_i^{\frac{2}{3}} I_{bi}^{\frac{1}{2}} \tag{3}$$

where U_i=average cross-sectional velocity, m/s; Q_i= discharge, m^3/s; A_i= cross-sectional area of the flow, m^2; n= roughness coefficient; R_i= hydraulic radius, $R=A/S$ (S is the length of the wetted perimeter), m; I_b= longitudinal gradient of the waterway, degrees.

$$B_i = \alpha \cdot Q_{spi}^{\ \beta} \tag{4}$$

where B_I=flow width, m; α and β are coefficients (set to α =4.0; β =0.5). On the basis of the previous disaster investigation date gained in the field, values of α and β are set from the flow width that roughly contains a house that was completely destroyed. The heights of the debris flow at the starting point of inundation and at each of the cross sections are calculated with Eq. 5 by means of the flow width, the peak flow rate of the debris flow, and the gradient of the land.

$$h_i = \left(\frac{n \cdot Qsp_i}{B \cdot (\sin\theta_i)^{0.5}} \right)^{\frac{3}{5}} \tag{5}$$

4) Delineating a "zone with a considerable danger of harm" is done by obtaining a force (F_d, kN/m^2) that is estimated to be applied to a building by the debris flow at the starting point of inundation and each calculation point by using Eq. 6, calculating the proof stress of the building at ordinary times (P_i, kN/m^2) by using Eq. 7, and by comparing these two values.

$$F_{di} = \rho_{di} \cdot U_i^2 \tag{6}$$

$$P_i = \frac{35.3}{H_i \cdot (5.6 - H_i)} \tag{7}$$

where H = height of debris flow, m. If the condition of $F_d > P_i$ is satisfied at the starting point of inundation, the zone from this point up to the calculation point at which the condition of $F_d \leq Pi$ has been met for the first time will be set as the "zone with a considerable danger of harm". Note that this system employs a method in which the end of the "zone with a considerable danger of harm" is obtained by means of repeated calculations carried out for each of the sections of 1 m. It has been decided to clearly distinguish those areas where the height of the debris flow exceeds 1 m and the force estimated to be applied to a building exceeds 50 kN/m^2 from those areas where the height of the debris flow exceeds 1 m but the force estimated to be applied to a building is less than 50 kN/m^2. Fig. 4 shows the results of delineating "zones with danger of harm" (Yellow Zone) and "zones with a considerable danger of harm" (Red Zone). In this system, visual verification has been made easy by displaying the result of hazard-zone designations on a digital elevation model (Fig. 5).

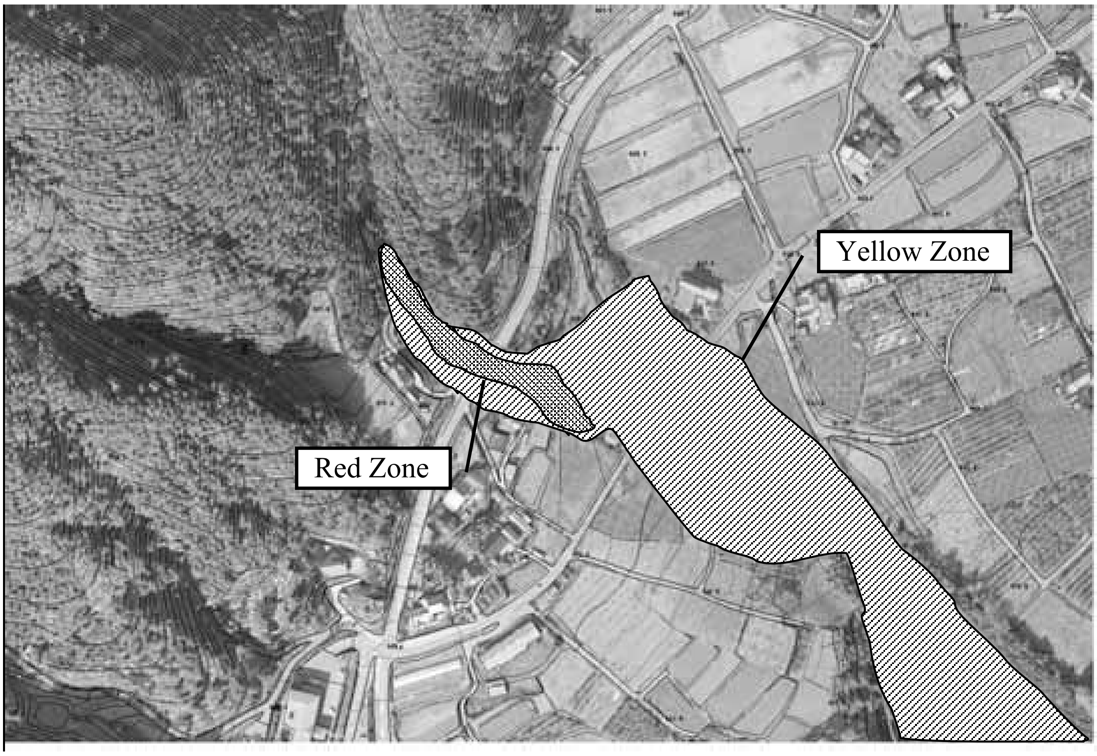


Figure 4. Result of setting zones by means of the system.

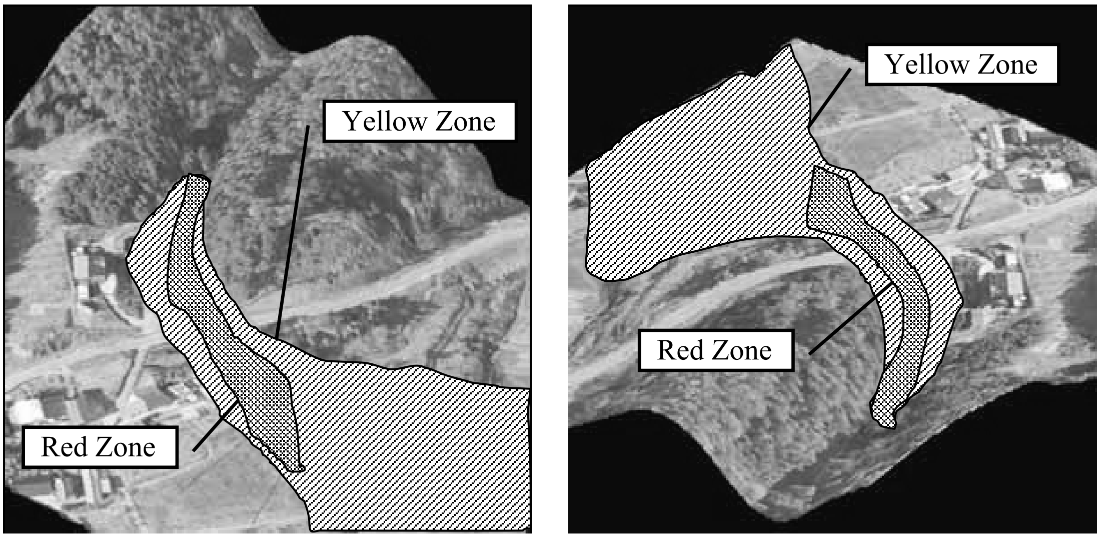


Figure 5. Hazard zones depicted on a digital elevation model.

4 OPERATION OF THE SYSTEM FOR DELINEATING DEBRIS-FLOW HAZARD AREAS

Since the system for delineating sediment-related hazard areas stores information on each zone as GIS data it can be used not only for sediment-related hazard areas but also for other work as well, such as city planning and depiction of zones subject to regulations by other laws related to disaster prevention and land use.

Also, since a mechanism has been developed to store in a database the three-dimensional topographical information that have been used for calculation, various types of parameters, and the results of hazard designations, those data can be referred to at any time and in the XML format. Therefore, even when they have been made available to the public, they can be fully utilized as explanatory materials when making a response to residents and claimants to the land.

As an evaluation of the operation of the zone-delineation system, a comparison of the accuracy of work and working time has been made with the case in which the same work has been done manually. Comparison shows that common mistakes made manually have been eliminated and the working time has been shortened by 90 percent. Also, since this system operates on a standard personal computer a large number of hazards assessment can be performed with accuracy and efficiency.

5 CONCLUSIONS

In this study we have described a methodology for delineating various debris-flow hazard zones efficiently and objectively. Our methodology makes use of three-dimensional topographical information and GIS technologies.

An evaluation of the system has verified that it is more efficient, objective, and reproducible than manually determining hazard zones. However, a high degree of accuracy in zoning is demanded for inhabitants in debris flow hazard zones. It is very important continuous on-the-spot inspections in the actual debris flow disaster areas. Depending on the flow-pattern of debris flows, the starting point of inundation must be changed. We must make every effort to get many data in the actual disaster areas.

ACKNOWLEDGEMENTS

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