1. INTRODUCTION

1-1 BACKGROUND AND OBJECTIVES OF THE STUDY

Landslides are among the most common natural hazards and are the most damaging, leading to a variety of human and environmental impacts. The identification of landslide affected areas and quantitative assessment of landslide hazard for a large area such as several tens of square kilometers, is critical to the mitigation of these loses. Such assessment is most essential for activities associated with the watershed management at different stages. This study develops the techniques of remote sensing and Geographic Information Systems (GIS; Burrough, 1986; Aronoff, 1989; Marble, 1990) in identifying areas affected by landsliding, assessing landslide hazard, producing landslide hazard maps, and evaluating these maps, and provides an example of a study area from Nepal.

Nepal is a country consisting of 83 percent hills and mountains, and steep terrain, fragile geology and seasonal monsoon rainfall all contribute to the occurrence of landslides. Every year, sediment-related disasters in Nepal result in an average loss of 400 lives and property losses amounting to US $ 17 million (Disaster Prevention Technical Center [DPTC], 1994). The impact is high during the catastrophic event. About 1,500 lives were lost, and 500,000 people were affected, along with a property loss of US $ 80 million (DPTC, 1994) from the sediment-related disaster which occurred on 19 July 1993 (Dhakal, 1995). The severity of the landsliding in Nepal can also be judged from the fact that as many as 20,000 landslide events have been estimated to occur in just one monsoon season (Ives and Messerli, 1981).

The objectives of this study are: (1) to develop methods of identification of landslide affected areas with the use of digital data obtained by Landsat thematic mapper sensor, (2) to develop the quantitative methods of landslide hazard assessment in GIS, and (3) to produce landslide hazard maps and to evaluate and examine the landslide hazard maps produced from different methods. The quantitative methods applied for hazard assessment are based on statistical analyses and are called Quantification Scaling Type II (Q-S II) analysis (Hayashi, 1952, 1980, 1987) and Failure rate (FR) analysis (Aniya 1985). The issues and approach employed to achieve the objectives are briefly discussed below and in detail in the sections 3-4-3 and 3-4-4.

This study should clearly show that the satellite remote sensing data and aerial photographs are appropriate at different stages of landslide hazard assessment and mapping. It should lead to a better understanding of landslide hazard assessment methods employed in GIS for large areas. Most importantly, the application of remote sensing and GIS techniques described should practically and effectively serve the hazard mitigation activities at different stages of the watershed management planning.

1-2 Remotely Sensed Data in Landslide Hazard Studies

Since landslide hazards result in highly variable damage, traditional approach of identification of areas affected by landsliding, and assessment and prediction of the impact is difficult and costly. The identification of "landslide affected areas" (after the event has occurred) is an important task right from the early assessment to the prediction of the disaster. The term "landslide affected areas" for mountain watershed, in this study, is used to denote the areas with any kind of slope movement (see section 3-1) phenomena, and areas associated with sediment deposition or flooding. Many landslide hazard assessment techniques usually rely on the evaluation of site characteristics of existing landslides, or land unit associated with landslides, for which mapping of landslide distribution is essential. Landslide distribution data is also necessary to test the simulated results of the physical model even if it is not required to develop the model. For large areas, mapping of landslides from the field survey only is complicated, time consuming, and costly. Remote sensing techniques, with their ability to cover a large area, have potential for mapping landslide distribution, and thus landslide hazard assessment.

Satellite digital remotely sensed data and aerial photographs are the most useful remotely sensed data available at present. The digital satellite data are suited for the detection of areas affected by landsliding, and for automatic mapping of those areas. The conventional aerial photographs are still the most important remote sensing means for landslide studies, allowing accurate mapping of individual landslides in large areas.

The identification of areas affected by landslides or an individual landslide from aerial photographs means that aerial photographs taken after the heavy rainfall, or both prior to and after the heavy rainfall are required. Aerial photographs taken on the required dates are often unavailable. For example, in Nepal so far there are only two sets of black and white photographs (1976; scale 1:50,000, and 1984 scale 1:40,000) that covers the entire Nepal (area 145,000 km^2), though a few more sets at a much larger scale are available for particular locations. The continuous availability of LANDSAT and SPOT satellite data, taken every 16 and 26 days respectively, gives the satellite data an important value for this kind of study. The interpretation of a single date LANDSAT and SPOT data has been found to be difficult for the identification of landslide affected areas (Aniya *et al.*, 1985b; Sakai *et al.*, 1985; Rangers *et al.*, 1992; Mantovani *et al.*, 1996). In a single date analysis of digital data, identification would be limited depending on the background contrast and the spatial resolution of the satellite data. In this circumstance, the multi-temporal satellite data captured prior to and after the heavy rainfall can be of great importance to perform pixel to pixel detection analysis of landslide affected areas. The land covers typically exhibit abrupt changes in spectral characteristics, both in the visible and outside the visible part of the spectrum, in response to disturbances. For example, the Landsat thematic mapper (TM) data contains seven bands (three visible, one infrared, two mid infrared, and one thermal band), and disturbances such as landsliding cause change in the brightness value (BV). However, so far no such detailed studies exist for the identification of landslide affected areas, and there are also insufficient studies that explore the appropriateness of using satellite digital data and conventional aerial photographs at different stages of landslide hazard assessment (see also section 3-4-3).

This study explores the methods of identification of landslide affected areas using multitemporal Landsat TM satellite data, in the visible, near infrared, and mid infrared ranges of the spectrum. The methods include 11 different algorithms from five different change detection methods (discussed in section 3-4-3 and 4-1-3). The five change detection techniques employed are (1) spectral image differencing (2) vegetation index image differencing (3) tasseled cap transformation image differencing (4) spectral change vector analysis, and (5) principle component analysis. The different change detection techniques are compared to determine the best technique in the identification of landslide affected areas. The conventional aerial photographs are also used for the production of the landslide distribution map.

1-3 GIS IN LANDSLIDE HAZARD STUDIES

The landslide distribution data extracted from remote sensing means such as aerial photos and satellite data, and brought into GIS, opens many possibilities of correlation studies between landslide distribution and thematic information stored in a GIS. GIS has overcome many of the difficulties normally associated with the handling of data in the study of geomorphic hazards (Dikau *et al.*, 1996). For example, Walsh *et al.* (1990), and Walsh and Butler (1997) used a GIS technique to illustrate morphometric characteristics of snow-avalanche paths and debris flow. Wadge *et al.* (1993) used GIS to evaluate risk associated with geomorphic hazards and population vulnerability. Various techniques using GIS for the assessment of landslide hazards have been employed by researchers (e.g., Gupta and Joshi, 1990; Mejia-Navarro *et al.*, 1994, Van Westen, 1994; Brunori *et al.*, 1995; Terlien *et al.*, 1995; Binaghi *et al.*, 1998; Dhakal *et al.*, 1999). Nevertheless, the studies that have used GIS in landslide hazard assessment remain limited, especially for large areas that can take full advantage of small grid-cell based raster GIS.

This study investigates the landslide hazard assessment, mapping and evaluation methods of hazard maps for large areas, addressing the different issues of small grid-cell based hazard assessment (see section 3-4-4 for detail discussion). Two quantitative methods called Quantification scaling type II (Q-S II analysis; multivariate statistical analysis) and FR analysis (Univariate statistical analysis) were employed for the landslide hazard assessment. In Q-S II analysis, five different combinations of samples of landslide and non-landslide group were used to examine the effects of the sampling methods on the critical factors and classes, and on the hazard maps produced from the results of the analysis (discussed more in section 3-4-4). Two cases in FR analysis were employed to clarify the effect of using frequency or area of landslides in the analysis. This is then followed by the production of a series of landslide hazard maps. The evaluation of accuracy and spatial agreement in these maps was carried out in order to compare the methods and to clarify the problem identified in the method. New methods of evaluation of landslide hazard map are introduced.