GIS application for comprehensive spatial landslides analysis in Kayangan Catchment, Menoreh Mountains, Java, Indonesia

D.S. Hadmoko, J. Sartohadi, G. Samodra & N. Christanto
Faculty of Geography, Gadjah Mada University, Bulaksumur, Yogyakarta, Indonesia

F. Lavigne
 CNRS UMR 8591, Laboratoire de Géographie Physique, University Paris 1 Panthéon Sorbonne, Paris, France

ABSTRACT: This paper provides a comprehensive analysis of landslide distribution in the Kayangan catchment, eastern part of Menoreh Mountains, Java, Indonesia. Raster-based GIS was applied in order to analyze the spatial distribution of landslides with parameters maps, e.g. slope, geology, geomorphology, drainage network, landuse, and road networks. 131 landslides were inventoried in the study area through internal reports of village offices followed by extensive field work. Four types of landslides were identified in the study area: slides, slumps, rockfalls, and flows. The landslides are distributed on a wide range of slope gradient and geological setting. Landslide density was 4.21 events.km$^{-2}$. Most of the landslides occurred on slope gradients ranging from 20 to 30° (35%), and were associated with roads. The landslides events were controlled not only by natural factors but also human activities mainly roads construction.

1 INTRODUCTION

Landslides, as one of the major natural hazards, cause each year a lot of casualties, property damage and economic losses in mountainous areas of the world (Dai, et al 2001). In Java for example, landslides caused an estimated 2,095 casualties and 552 wounded people during the period of 1981 – 2007 (Hadmoko et al., 2008). It was also estimated that 67,000 people had to be evacuated because of the destruction of their houses and the hundreds of threatened villages. At present, such damage and casualties seems to be increasing, mainly because of an increase of population growth and urbanization at hazardous locations, so that landslide hazard mitigation program should be addressed.

In order to conduct proper landslide mitigation, comprehensive information of spatial characteristics of landslides is necessary (Van Westen et al. 2005; Van Westen et al. 2008). This information is vital mainly for landslide hazard and risk assessment (Remondo et al. 2005; Gorsevski et al. 2006). In addition, analyzing the relationship between landslide distribution and terrain parameters not only provides an insight into our understanding of landslide mechanisms, but can also form a basis for predicting future landslides (Zhou et al. 2002).

Geographic Information Systems (GIS) are widely used in spatial landslide studies (van Westen, 1993; Huabin et al. 2005). In regard to spatial landslide analysis, GIS is an important tool to carry out data input, handling, visualization, combination, query, analysis, and output (Burrough, 1986). GIS is used to handle the spatial distribution of terrain parameters, to determine spatial-mathematical modeling in relation between terrain parameter within the distribution of landslides. In addition, GIS can be helpful to build landslide hazard maps for various input scenarios.

This paper deals with the spatial distribution of landslides and their linkage with terrain factors e.g. geology, slope, elevation, drainage network, landuse and road network. The relationship between landslide distribution and terrain factors is inherently nonlinear, and varies spatially. In addition, the study area currently lacks of any kind of landslide investigation, therefore this research would be a pioneer that established integrated analysis on landslide event. Consequently, this research is necessary to understand the influence of terrain factors to landslides which would be useful for hazard assessment.

2 STUDY AREA

Kayangan Catchment is situated on the eastern flank of Menoreh Mountains, Yogyakarta Province, in Java Island (Fig. 1). With area of 31 km$^2$, the study area is characterized by complex terrain and dominated by hilly and mountainous area with the elevation ranging from 49 – 825 m.
Geologically, Kayangan catchment consists of 5 geological formations e.g. Kebobutak Formation (andesitic breccias, tuff, lapilli tuff, aggromelare and andesitic lava flows), Jonggrangan Formation (conglomerate, tuffaceous marl and calcareous sandstone, limestone and coralline limestone), Nanggulan Formation (sandstone with intercalated of lignite, sandy marl, claystone with limonite concretion, intercalations of marl and limestone, sandstone, and tuff); Sentolo Formation (limestone and marly sandstone); old andesit; colluviums; and alluvium (Rahardjo et al., 2005) The geodynamic activities were relatively active and represented by several major faults encompassing the study the area.

Because of a strong orographic effect, annual precipitation is extremely variable, and ranges from about 2500 mm/year to nearly 4000 mm.yr\(^{-1}\). Due to the wet tropical climate setting with a relatively high temperature environment, denudational process e.g. weathering, erosion and landslides is very intensive in most lithological settings (Hadmoko et al. 2008).

3 METHOD

In order to achieve the objectives of the research, several methods have been applied through three steps: landslides inventory and mapping, preparation of terrain parameter maps, analysis of the relation between landslide distribution and terrain parameter maps.

Landslide inventory and mapping have been conducted from various sources of data as follows: (1) previous reports and internal database of district and village offices, and (2) aerial photos and satellite image interpretation in order to recognize and identify the trace of landslide bodies and (3) a number of extensive fieldwork have also been conducted in order to check the validity of image interpretation and to measure the landslide morphology. All the information concerning the type, length and width of landslide bodies was also entered in database.

Mobile GIS has been applied during data acquisition in the field in order to enter all the information directly in the database. This technique is necessary to reduce the time consuming during post fieldwork. In addition, participatory GIS (P GIS) was used in order to map the non identifiable landslide features through the experiences of local people. This method was very helpful to inventory most of landslides which have already reworked by local peoples or local authorities.

We obtained terrain parameter maps from various sources of data. The lithological map was derived from existing geological map (1:50,000) (Rahardjo et al., 2005). The slope map was obtained from a digital topographical map delivered by the National Agency of Survey and Mapping (1:25,000) (Bakosurtanal, 1997). In order to obtain the slope map and elevation map, a raster based DEM has been built by applying kriging interpolation in ILWIS software version 3.4. Drainage network, landuse map and road network map were obtained directly from an existing digital map (Bakosurtanal, 1997). We applied buffer analysis in order to classify the distance from roads and from drainage networks. Six classes of distances have been used in this research i.e. 0 – 25 m; 25 – 50 m, 50 – 75 m; 75 - 100 m; 100 – 125 m; 125 – 150 m and > 150 m. We conducted buffer analysis in order to understand the contribution of drainage network and road network to landslide events.

Spatial analysis of landslides distribution has been conducted by overlaying the landslide distribution map with each terrain parameter map separately. The number and density calculation for each variable in the terrain parameter maps has been done separately in order to know the contribution of each variable on landslide occurrence.

4 RESULT AND DISCUSSION

4.1 Spatial distribution of landslides

A total of 131 landslides were mapped in the whole area of Kayangan Catchment. They are distributed over a wide range of terrain conditions (Fig. 2). The number density and area density of landslides reached a value of 4.21 events.km\(^{-2}\) and 4 x 10\(^{-3}\) km\(^{2}\).km\(^{-2}\) respectively. Most of them are situated on the upper and middle zone of catchment while landslide is absent in the lower part of Kayangan catchment due to the flat terrain morphology. All land-
slides in the study area were considered as shallow landslides which had typically a depth of the slip surface smaller than 5 meters and an average surface of 968 m².

Figure 2. Spatial distribution of landslides in Kayangan Catchment.

The types of observed landslides were classified according to the system of Varnes (1978), which takes types of movement and materials into account. Based on field observations, five types of landslide were identified i.e. soil creep, earth flow, rockfall, slide and slump. Among the 131 landslides in study area, most of them were classified as slides, and followed by slumps, creeps, flows and rockfalls with the frequency of 94; 26; 4; 4; and 2 respectively. Their lengths are usually longer than widths and they are characterized by clayey materials.

4.2 Spatial distribution of terrain parameters

Five terrain parameters were mapped for the study area. We classified and calculated the surfaces of all variables in terrain parameter maps (Fig. 3) in order to calculate the landslide density. The study area is dominated by the elevation range below 100 m (6.05 km²) which is distributed in the southern zone of Kayangan Basin. Slope classification indicated that the biggest proportion of slope inclination was 0 – 10° (10.7 km²) which distributed in the lower part of drainage basin (Fig. 4).

According to the buffer map of stream networks, the study area is dominated by the distance more than 150 m from stream network (13.28 km²) while the area with the distance 125 – 50 m covered only a small area of the study area (2.9 km²). Regarding to landuse types, Kayangan Catchment is dominated by mix garden which distributed on a wide range of terrain conditions (17.7 km²). Mix garden consists of coconut trees, cloves, bamboos and other types of hard trees. They are usually associated with settlements which covered 3.3 km². Agricultural activities are also dominant in Kayangan Catchment, and represented by the surface of dryland agriculture (9.3 km²) and ricefield (4.5 km²). Regarding to road networks, the study area is occupied by relatively good condition of roads even in the village area. Buffer class of road networks showed that study area is dominated by a distance of more than 150 m (10.02 km²).

Figure 3. Surface of terrain parameters in the study area versus geology (a), elevation (b), slope (c), distance from stream (d), (e) landuse, and distance from road (f).

4.3 Analysis of landslides and terrain parameters

Analysis of landslide activities and geological formation showed that only two types of lithologies were subjected to landslide occurrence: Kebobutak Formation and Jonggrangan Formation. Most of them occurred in the Kebobutak Formation (119 events) and followed by Jonggrangan Formation (Fig. 5a, b). Most of landslides occurred on Kebobutak Formation because this formation covered the largest area of study area (25.83 km²) which leads the high probability of landslides.
In addition, the strong weathering and fracturing of the andesite and andesitic breccias play an important role on landslides predisposition. Twelve landslides were identified in Jonggrangan Formation mostly in calcareous sandstone and limestone. Landslides are absent in other type of rocks because they cover only a small proportion of study area and are situated at the southern and eastern part of Kayangan Catchment with flat relief.

The relationship between landslide occurrence and slope (Figs 5c, d) shows that steeper slopes have greater landslide frequency up to a slope steepness of 20 – 30°. The highest density of landslides both for number density and area density can be found on moderately steep terrain, ranging from 20° to 30° (0.047 events.km⁻² and 7 km².1000km⁻²). However, inverse correlation between landslides events occurs on slope steepness more than 30° when the landslide frequency decreases with an increasing of slope angle. This result is slightly similar with those in the Mt. Aso, Japan (Paudel et al. 2000) and in the Upper Tiber River basin, Central Italy (Guzzetti et al., 2008). Their results showed that the landslide frequency is highest for slope angles ranging from 20° to 30° and tends to decline with an increasing or decreasing slope angle.

Theoretically, as the slope angle increases, the shear stress in the soil or other unconsolidated material generally increases and the landslide probability increases (Lee & Pradan, 2006). Gentle slopes are expected to have a low frequency of landslides because of the generally lower shear stresses associated with low gradients. However, this case is not always applicable for all type of terrains. In Kayangan Catchment for example, several landslides incidents can be found on the gentle –moderate (less than 20°) due to the role of other factors disturbing slope stability such as human activities (Paudel et al., 2000; Guzzetti et al. 2008). Very steep slope is sometimes absent from landslide activities because of the existence of resistant bedrocks and consolidated materials. These usually consist of non-arable land leading to the fewer human activities.
by unconsolidated materials like colluvium, which is more prone to landslides.

Figure 6. Number of landslides, landslides area and landslide density for distance from stream (a-b), landuse (c-d), and distance from road (e-f).

Regarding to landslide frequency and stream network buffers revealed that most of landslides were situated a distance more than 150 m from rivers (46 events which equal to 3.46 events/km²) (Fig. 6 a, b). Only 14 landslides were mapped in the zone of less than 25 m from rivers. There is no trend indicating decreasing of landslide frequency with the increasing distance from rivers. However, the landslide area is highest in the buffer zone less than 25 meters, it indicates that most of bigger landslides were situated near the rivers due to the slope modification by gully erosion which influences the initiation of landslides. This result is slightly different from Dai & Lee (2002) who found that as the distance from drainage line increases, landslide frequency generally decreases.

Analysis of landslide occurrence based on landuse type showed that there are only 3 types of landuses affected by landslides e.g. mix garden, settlement and dryland agriculture (Fig. 6 c, d). Mix garden is the most exposed landuse to landslide (72 events) with the number and area density reached 4.06 events/km² and 6.2 km²/1000km². However, the highest number and area density of landslides was identified in settlement with the value of 11.028 events/km² and 10.8 km²/1000km² respectively. The spatial distribution of landslide on most of manmade terrain underlines the human contribution on landslide triggering.

In order to assess the contribution of human activities to landslides, we analyzed landslide frequency at each distance from road networks (Fig. 6e, 6f). The majority of landslides occurred on the zone which closest to road networks (< 25 m). 83 landslide events (63 % of total landslides) have been mapped in this area with the number density and area density reached 36.55 events/km² and 28 km²/km² respectively. In general trend, landslide events decrease with the increasing the distance from road. This trend reveals that road networks play an important role in landslide initiation. These kind of human activities have initiated and accelerated landsliding in this region particularly via the undercutting and removal of the toe of slopes for the cutting of roads and houses. Due to the land limitation and low risk perception, local peoples built their house on the steep slopes (Fig. 7). A comparable case occurred in Garhwal Himalaya, India, that human activity has influenced about two-thirds of the active landslides, and therefore human-influenced landslide is helping to accelerate denudation in this part of the Himalaya (Barnard, et al. 2001).

5 CONCLUSION

Comprehensive analysis of landslide and parameter maps revealed that physical-natural factors (geology, slope, elevation, and distance to networks) and human activates contribute to landslide occurrence in study area. However, these terrain parameters have different level of contribution to landsliding which
were indicated by frequency and density of landslides on each terrain parameter. We found that human activities play an important role in landslide acceleration particularly through slope cutting for houses and road construction.

The study area currently lacks of any kind of landslide investigation, therefore this research could be a pioneer that established analysis between landslide and terrain parameters. This research would be a basis for future landslide susceptibility and hazard assessment. Qualitative and quantitative landslide probability analysis could be carried out by using this data by applying different methods. Finally, this research could be useful as one component for the landslide risk management.

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REFERENCES


