Application of supervised landform classification of 9-unit slope model for preliminary rockfall risk analysis in Gunung Kelir, Java

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Abstract—**Rockfall risk analysis requires assessment of susceptibility and identification of elements at risk. To portray the susceptible area, the opinion of geomorphologists is commonly used to classify landforms through interpretation of aerial photos and field survey. However, the subjectivity of investigators hinders application of this method. Therefore, supervised landform classification is applied in the present study, based on relevant parts of the 9-unit slope model. The main objective is to provide automated landform classification particularly for rockfall analysis. This is achieved in five stages: 1) fieldwork , 2) DEM preprocessing, 3) DEM processing, 4) rockfall modeling, and 5) landform classification based on fuzzy k-means. The result reveals that potentially high risk is located in the transportational middle slope and colluvial footslope. This is useful information on which to base prioritization action for countermeasures, both policy and design. The application of supervised landform classification in Gunung Kelir provides a reasonable result for preliminary rockfall risk assessment.**

I. INTRODUCTION

Along with the increasing loss of life and property due to rockfall, awareness toward the need for rockfall risk management has recently greatly increased. Here, geomorphometric analysis can be used as a tool for incorporating disaster risk reduction and transfer measures into development planning. This provides basic ideas for planning priorities in promoting risk management plan and strategy, and evaluating spatial planning policies. Thus, by using geomorphometry as a preliminary tool for risk assessment, the spatial planning manager can make a balance between minimizing risk and promoting some development priorities.

Selection of preventive mitigation measure type, structural protection location and structural protection dimension should be supported by rockfall risk assessment based on geomorphologic analysis. The 9-unit slope model [1] i.e. interfluves, seepage slope, convex creep slope, fall face, transportational midslope, colluvial footslope, alluvial footslope, channel wall and channel bed; can pose important zones of mass movement process where energy and velocity are diverse in places. It can be delineated into a key information for prioritization of mitigation actions. The information is useful to expose the spatial distribution of potentially high damage of elements at risk affected by rockfall.

Traditionally, landform delineation and classification are based on the stereoscopic technique of aerial photo and field investigation. This method is very common in Indonesia. It has been applied for soil mapping, land evaluation analysis, land suitability analysis, spatial planning, and so on. There is also mentioned in Indonesia's National Standard document of Geomorphological Mapping that the technical requirement for geomorphological mapping is an interpretation of remote sensing data combined with field measurement [2]. The standard landform classification in Indonesia is ITC System [3]. However, the traditional method in landform classification requires simultaneous consideration and synthesis of multiple different criteria [4] and the quality depends on the skill of interpreter. Thus, we try to automated classify landform based on the 9-unit slope model which seems more appropriate to rockfall analysis. Even though, the 9-unit slope model is significant for pedogeomorphic process response [5], it is also capable to explain rockfall deposition.

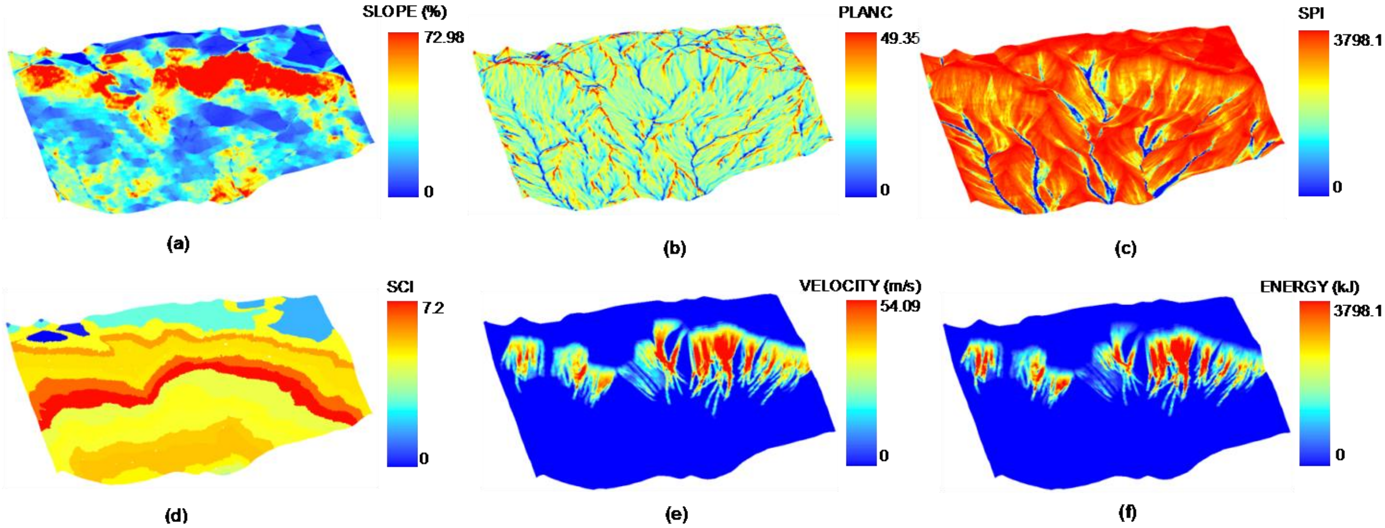

Figure 1. Morphometric variables derived in ILWIS (a) slope, (b) plan curvature (c) stream power index (d) shape complexity index and morphometric variables derived in ArcGIS (e) rockfall velocity (f) rockfall energy

II. STUDY AREA

Gunung Kelir is located in Yogyakarta Province, Indonesia. It lies in the upper part of Menoreh Dome that is located in the central part of Java Island. The area is dominated by Tertiary Miocene Jonggrangan Formation that consists of calcareous sandstone and limestone. Bedded limestone and coralline limestone which form isolated conical hills may also be found in the highest area surrounding the study area. *Gunung* (Mountain) *Kelir*, of Javanese origin, literally means a curtain that is used to perform *wayang* (Javanese traditional puppet). Its toponym describes a 100-200 meter high escarpment that has maximum slope nearly 80°.

Landforms in Gunung Kelir are a product of final uplifting of the Complex West Progo Dome in the Pleistocene [6]. Slope gradient varies between 0° and 80°, meanwhile mean of slope gradient is 23.14° with the standard deviation 13.05°. Altitude ranges from 297.75 to 837.5 m. There are 152 buildings exposed as elements at risk on the lower slope of the escarpment. Some cracks have been found in the upper part of Gunung Kelir after Yogyakarta Earthquake 2006. Nowadays, the local government is still working to anticipate the worst scenario of rockfall hazard in Gunung Kelir area.

III. DATA AND METHODS

Fieldwork activity, DEM preprocessing, DEM processing, rockfall modeling, and landform classification were carried out in this study. Fieldwork was intended to identify rockfall boulders and elements at risk. A field inventory of fallen rockfall boulders of different size has been done to obtain the spatial distribution and dimension of rockfall deposition. The dimension and potential rockfall source were determined to simulate rockfall trajectory, velocity, and energy. The buildings on the lower slope of the escarpment were also plotted in order to obtain the spatial distribution of elements at risk. Finally, DGPS profiling was conducted to improve performance of DEM.

The objective of DEM preprocessing was to improve the quality of DEM-derived products. We applied DEM preprocessing proposed by Hengl et al. (2004) [7] including reduction of paddy terraces, reduction of outliers, incorporation of water bodies, and reduction of errors by error propagation. DEM was produced by interpolation from a 1:25.000 Topographical Map with contour interval 12.5 and elevation data from the DGPS profiling. DEM processing generated several morphometric and hydrological variables such as slope, plan curvature, SPI (Stream Power Index) and SCI (Shape Complexity Index) (Figure 1). DEM-derived products were processed in ILWIS software with several available scripts in Hengl et al. (2009) [8].

The other morphometric variables were rockfall velocity and energy. There were processed by RockFall Analyst as an extension of ArcGIS [9]. It included modeling of rockfall trajectory by kinematic algorithm and raster neighbourhood analysis to determine velocity and energy of rockfall. Rockfall velocity and energy analysis needed information of slope geometry and other parameters such as mass, initial velocity, coefficient of restitution, friction angle and minimum velocity offset. Slope parameter was derived from corrected DEM. The other parameters were derived from secondary data and field data. For example, coefficient restitution and friction angle were derived from literature review based on landuse map and geological map, whereas mass was determined from the dimension of boulders derived from field data measurement. The result was validated with the spatial distribution of boulders inventory obtained from fieldwork.

The landform elements were derived, as the 9-unit slope model, by using the supervised fuzzy k-means classification [10] as

$$\mu_{ic} = \frac{\left[(d_{ic})^2\right]^{-1/(q-1)}}{\sum_{c'=1}^{k}\left[(d_{ic})^2\right]^{-1/(q-1)}} \tag{1}$$

where µ is the membership of *i*th object to the *c*th cluster, *d* is the distance function which is used to measure the similarity or dissimilarity between two individual observations, *q* is the amount of fuzziness or overlap (q=1.5). Supervised k-means classification was written and applied in ILWIS script. Modified 9-unit slope model was applied by excluding alluvial toe slope and seepage slope into a final landform classification.

IV. Result and Discussion

Geomorphometry defined as a quantitative landform analysis [11] was initially applied for the assessment and mitigation of natural hazard [12]. Dijke and Westen (1990) [13], for example, introduced rockfall hazard assessment based on geomorphologic analysis. Later, Iwahashi et al. (2001) [14] analyzed slope movements based on the landform analysis. Both utilized DEMs derived from interpolation of 1:25.000 scale contour map to analyze geomorphological hazard. Nowadays, the interpolation of contour map is still powerful to create medium scale mapping when better resolution DEMs are not available. However, reduction of error in interpolation is needed to obtain plausible geomorphological feature.

Reduction of paddy terraces, reduction of outliers, incorporation of water bodies, and reduction of errors by error propagation were applied in this study to improve the performance of DEM. The result shows that paddy terraces still exist where the sampling of elevation data are absent. In addition, “flattening” topography can also be found on slopes less than 2%. Remaining paddy terraces mostly occur in the transportational middle slope and flattening phenomenon mostly occurs in the interfluves. Both errors influence the plausibility of slope, (Figure 1a) but those do not much influence the final classification of landform elements.

DEM processing was divided into two parts, i.e. morphometric variables derived from ILWIS script and morphometric variables derived from RockFall analyst. Rockfall velocity and energy are second derivative of DEM [9]. The first derivative DEM i.e. slope angle and aspect angle were employed to compute the rockfall trajectory. Then, rockfall trajectory was used to model the rockfall velocity and rockfall energy by using neighborhood and geostatistical analysis. The highest velocity occurs in the fall face and transportational middle slope. Velocity gradually decreases in the colluvial footslope. Since the energy is also calculated from rockfall velocity, the spatial distribution pattern of energy is rather similar to rockfall velocity. Both velocity and energy of rockfall influence the area of fall face, transportational middle slope and colluvial footslope. The first change of a pixel into zero velocity and energy of its neighborhood operation is determined as the end of boulder movements. It means that the rockfall boulders are deposited on this site. Plan curvature and stream power index influence the pattern of the convex creep slope and the channel bed. It forms water divide and stream channel. SCI, sliced using an equal interval 25 m, was measured as the complexity of outline of 2-D object. It predominantly influences the spatial distribution of the interfluves. Its effect on the other landforms is not apparent because the value of SCI in the lower slope is relatively homogeneous e.g. 4-5.

The result of the model is qualitatively evaluated with the boulders inventory obtained from fieldwork activities. The boulder deposit is located on the lower slope of the transportational middle slope and colluvial foot slope. Thus, the most susceptible place for rockfall hazard is fall face, transportational middle slope, and colluvial footslope respectively.

Preliminary rockfall analysis can be delivered by evaluating elements at risk located in the susceptible place for rockfall hazard. There are 3 buildings located on the transportational middle slope and 14 buildings located on the colluvial footslope. This is useful information on which to base prioritization action for countermeasures policy and design. Geomorphologic analysis should be taken into account to locate structural measures (e.g. barriers, embankments, rock sheds) in suitable location. It will improve cost efficiency to optimize budget and design. The information of building located on the landform classified as high hazard can also be an input to the prioritization of evacuation procedure. Therefore, the prioritization of mitigation action based on geomorphometric analysis can meet the technical suitability and the effectiveness of selected mitigation options.

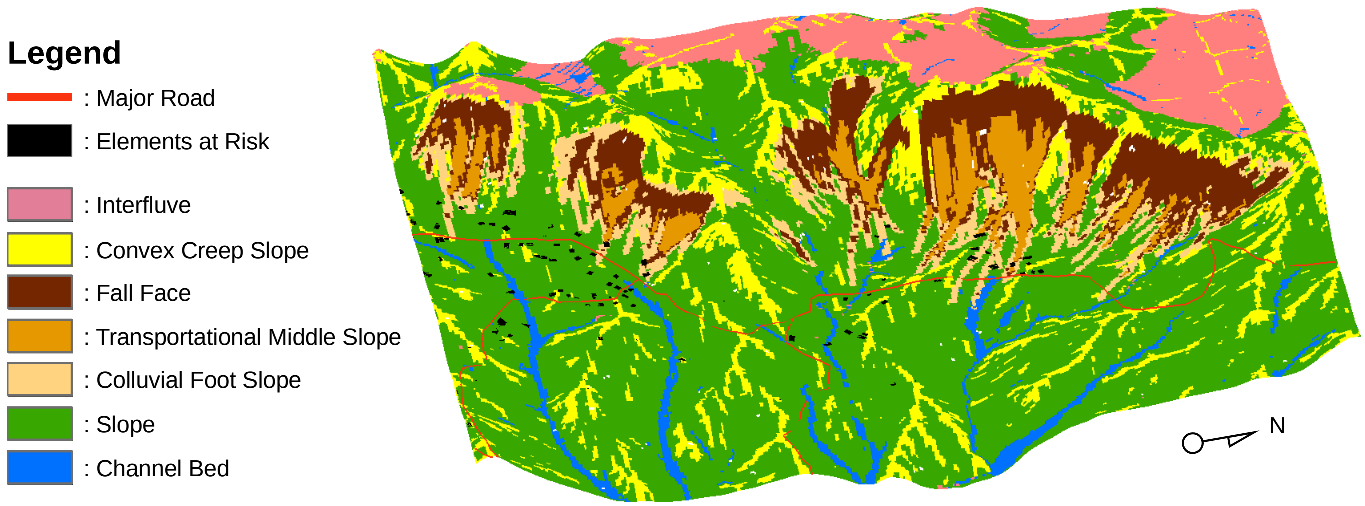

Figure 2 Generic Landforms in Gunung Kelir

However, the classification of 9-unit slope model should be modified if it is applied in different places. The final classification of landform elements i.e. interfluves, convex creep slope, fall face, transportational middle slope, colluvial footslope, slope and channel bed (Figure 2) is different with the original classification of the 9-unit slope model. Alluvial toe slope and seepage slope were excluded from the final landform classification in the present study. Channel wall was also modified as slope. Since the study area is located in the upper part of Kulon Progo Dome, the depositional process of alluvium does not work in that such area. Seepage slope was merged with interfluves slope because interfluves slope and seepage slope landform classification is more related to pedogeomorphic process rather than gravitational process. The considerations to merge and exclude some landforms were based on the experience and the judgement of researchers.

V. Conclusion

Geomorphometry application can be an alternative tool to minimize the subjectivity of Indonesia's standard landform classification applied in disaster risk reduction. Application of supervised landform classification in Gunung Kelir provides reasonable result for preliminary rockfall risk assessment. Landform analysis should be taken into account in disaster risk reduction design and planning. Further studies should explain the effects of scale and spatial dependency on the landform classification.

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