

LANDSLIDE SUSCEPTIBILITY MAPPING WITH HEURISTIC APPROACH IN MOUNTAINOUS AREA A CASE STUDY IN TAWANGMANGU SUB DISTRICT, CENTRAL JAVA, INDONESIA

S.E. Wati^{a,*}, T. Hastuti^a, S. Widjojo^a, F. Pinem^a

^a Center for Atlas, National Coordinating Agency for Surveys and Mapping (BAKOSURTANAL)
Jakarta Bogor Street Km. 46, Cibinong, Bogor, West Java 16911 Indonesia
ekaceria24@gmail.com

KEY WORDS: Landslide, Susceptibility, Heuristic, Weight, Score, Tawangmangu

ABSTRACT:

Landslide susceptibility mapping is one of the required activities in landslide prone area. This is intended to recognize the spatial probability of landslide as an action to minimize the upcoming impact. Landslide susceptibility map can be used as supporting information in spatial planning process as well, particularly in restricting landslide prone area as free of development zone. Currently, landslide susceptibility mapping had not been done yet in Tawangmangu Sub District. In fact, this area was often suffered by landslide. Thereby, this research was focused on generating landslide susceptibility map for this area in order to improve the current spatial plan and to guide local government in managing present and future land utilization

Landslide susceptibility information was developed by harnessing heuristic approach with weighted-score method. Six parameters utilized were slope, lithology, soil depth, texture, permeability, and land use. Some parameters related to soil properties were obtained from field survey with landform based while land use information was achieved from visual interpretation of Ikonos imagery followed by field checking. All parameters were assigned a certain weight and score based on expert judgment. The weight was automatically processed through rank method which is available in ILWIS (Integrated Land and Water Information System) software whereas the score was given in the range of 1 – 4. Apart from that, landslide inventory mapping was also conducted by visual interpretation of Ikonos imagery and field survey.

Study area is mostly classified as high and very high susceptible zone (50%). Moreover, 36% of total study area is categorized as moderate susceptible to landslide. The rest area is included in low and very low susceptible zone. Based on this result, it can be also identified that more than one third (47%) of settlement area in this location is situated under landslide threat. It is only 25% of total settlement area located in very low and low susceptible zone. To overcome this circumstance, the comprehensive landslide mitigation strategies must be developed to enhance the recent landslide mitigation activities and to supplementary reduce the possible damages and destructions.

1. INTRODUCTION

Indonesia is one of disaster prone areas in the world. It is located in the meeting point of three dynamic plate tectonics, i.e. Pacific plate, Indo-Australian plate, and Eurasian plate. Also, it is situated in dangerous zone, known as Ring of Fire. Due to those conditions, earthquake, volcanic eruption, and other secondary disasters often occur. One of secondary disasters is landslide. Landslide is triggered whether by earthquake or by excessive rainfall. Since Indonesia is positioned in tropical zone with six month wet season; landslide frequently takes place.

The existence of landslide event reveals the need to recognize the landslide characteristics, particularly in terms of mechanism and its spatial probability. The spatial probability of landslide event itself can be identified through landslide susceptibility mapping. Landslide susceptibility basically can be defined as quantitative and qualitative assessment including

classification, volume, and spatial distribution of landslides which exist or potentially occur (Fell et al, 2008). Based on this definition, the susceptibility gives a description of existing and potential landslide in which landslides frequently occur in the most susceptible area. In terms of susceptibility, time frame is not explicitly considered and the susceptibility analysis brings the information about combination of several physical factors influencing landslide occurrence in a certain location.

Tawangmangu Sub District is located in the frontier area between Central Java and East Java Province. This region is a part of Lawu Volcano area. The volcanic activities in Pleistocene and Holocene Period affect the physical appearance of this area. The existing features are deep soil, steep slope, slow up to fast permeability, and also clay and loam texture. In case of lithology, this location is mainly formed by volcanic rock and andesitic lava. Incompact material because of the high amount of sand makes this location more vulnerable to land

* Staff of Center for Atlas, National Coordinating Agency for Surveys and Mapping (BAKOSURTANAL), ekaceria24@gmail.com

movement activities. Study area is already intensively harnessed as settlement area and agricultural land especially vegetable garden. Furthermore, this area has quite high rainfall intensity rather than surroundings as well. The amalgamation of present situations drives landslide events in this location. At least, 39 landslides were found during the field work. These events generally caused casualties, damaged houses, roads, and agricultural lands. Thereby, landslide susceptibility mapping in this area is urgently required to determine the landslide prone area and to help the government and community's efforts in reducing landslide effects.

2. METHOD

2.1 Data

Necessary data for this research consist of slope, lithology, soil depth, soil texture, soil permeability, and land use. Those data were compiled from several sources, i.e. topographic map scale 1:25,000, geological map scale 1:100,000, satellite images (Landsat ETM 2001 and Ikonos 2006), SRTM (Shuttle Radar Topographic Mission), and field survey (see Figure 1). Field survey was conducted to obtain several primary data related to soil properties (depth, texture, and permeability), land use, and the location of landslide events. The data of landslide location were previously collected from local offices in the level of regency, sub district and village.

The field survey was carried out regarding to landform approach. Landform was generated by combining DEM (Digital Elevation Model) of SRTM and Landsat ETM to create 3d view. The developing process of 3d view used Erdas Imagine software. The visual interpretation stage of 3d view was then supported by contour and geological map. As a result, study area was divided into 13 landforms, as follow:

- Volcanic cone of Lawu Volcano (*vc1*).
- Lower slope of Mount Sidoramping (*lss*).
- High hill in Sidoramping lava flow (*hhs*).
- Moderate hill in Sidoramping lava flow (*mhs*).
- Low hill in volcanic rock formation (*lhv*).
- Undulating terrain in lava flow (*utl*).
- Small valley in Sidoramping lava (*svs*).
- River valley (*rv1*).
- Eroded volcanic cone (*evc*).
- Front slope of Lawu Volcano (*fs1*).
- Lawu lahar plain (*llp*).
- Andecite hill (*adh*).
- Limestone hill (*lsh*).

2.2 Landslide Susceptibility Analysis

Landslide susceptibility can be developed through several methods. Those are statistic, deterministic, and heuristic. All method is usually started by landslide inventory mapping as a basis in validating the obtained landslide susceptibility map. In

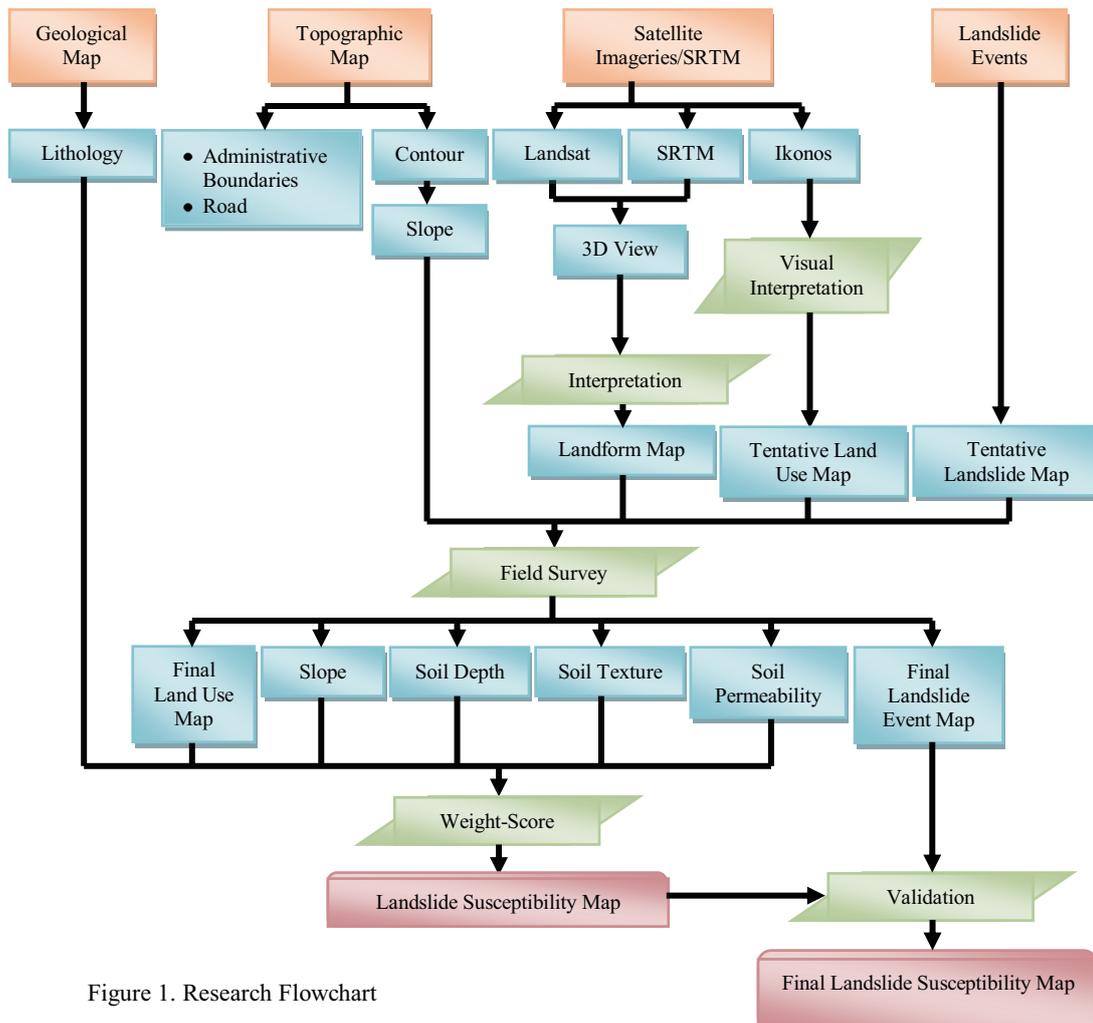


Figure 1. Research Flowchart

this research, landslide susceptibility was examined by heuristic approach with weighted-score method. The weighted and score was determined by expert judgment in which it represents the effect of each parameter in the mechanism of landslide occurrence. The higher the weight and score depicts the higher the influence of a given parameter in causing landslide event. The weight was achieved from rank method which was automatically generated in ILWIS (Integrated Land and Water Information System). On the other hand, the score was presented in the range of 1 – 4. The susceptibility analysis was technically conducted by harnessing ArcGIS 9.2 and Arcview 3.3 software.

Six parameters were employed in landslide susceptibility analysis, i.e. slope, lithology, soil depth, texture, permeability, and land use. Rainfall parameter was not taken into account because the study area is quite small and the rainfall intensity in this region is relatively similar. The determination of weight and score for every parameter as illustrated in Table 2 considers the following assumptions:

- Slope is the main factor that affects in increasing shear stress and also reducing shear strength. The higher of the slope is associated with the higher of the shear stress. It means that the probability of failure is getting bigger.
- Lithology is parent material. It plays a role as slip surface. The hard and massive rocks are generally resistant to erosion (Anbalagan and Singh, 2001), e.g. andecite and limestone. Andecite and Wonosari formation (limestone) are set up with the lowest score. On other sides, Lawu lahar and Jobolarangan breccia are more brittle than lava formation (Jobolarangan lava, Sidoramping lava, Candradimuka lava) due to the high amount of sand fragment. Apart from that, rock composed by sandstone is more vulnerable to erosion so that it is more susceptible to landslide. Lawu volcanic rock is geological formation formed by sandstone material.
- Soil is mass block upon parent material. Soil depth influences the shear stress and shear strength. The depth of soil is associated with the weight of soil. It is assumed that the deeper the soil, the weightier the mass. Thus, the higher score is allocated to the deeper soil.
- Soil texture is the weight proportion of the separates for particles less than 2 mm. The texture can be recognized from a laboratory particle-size distribution (USDA, 1993). The soil with fine texture (clayey soil) has small pores and liberates the water gradually. It means that clayey soil is easier to be saturated than sandy soil. Hence, clayey soil is more susceptible to landslide because this soil can retain more water. This condition causes the increasing the weight of soil mass.
- Soil permeability is related to soil texture. The clayey soil is more vulnerable to landslide because it has lower permeability than silt and sandy soil. Therefore, the slower the permeability represents the higher the possibility of landslide.
- Land use is an indirect indicator of slope stability (Anbalagan and Singh, 2001). Sparse vegetation enhances the effect of weathering and erosion. House construction in settlement area also enlarges weight to the slope (Smith, 2001). Vegetable garden in steep slope area increases the susceptibility of landslide as well. Regarding to lithology, limestone area are less prone to landslide. Paddy field is also resistant to erosion and landslide as if it is located in flat area.

The susceptibility level was ultimately classified into five classes, i.e. very low, low, moderate, high, and very high based on the accumulative weighted score. The class division was done by natural break classification. In this case, the accumulative score was grouped according to its natural distribution.

Table 2. Weight and Score of Landslide Susceptibility's Parameter

Parameter and Weighted Factor	Score
Slope → Weight: 40.8	
Flat and undulating (0 – 8%)	1
Moderately sloping (8 – 15%)	2
Hilly and moderately steep (15 – 45%)	3
Steep (>45%)	4
Lithology → Weight: 24.2	
Andecite, Wonosari formation	1
Jobolarangan lava, Sidoramping lava, Candradimuka lava	2
Lawu lahar, Jobolarangan breccia	3
Lawu volcanic rock	4
Soil Depth → Weight: 10.3	
Very shallow (<25 cm)	1
Shallow (25 – 50 cm)	2
Moderate (50 – 90 cm)	3
Deep (>90 cm)	4
Soil Texture → Weight: 6.1	
Sandy loam, loamy sand, and sand	1
Loam, silty loam, and silt	2
Sandy clay loam, clay loam, and silty clay loam	3
Sandy clay, silty clay, and clay	4
Soil Permeability → Weight: 2.8	
Moderately fast, fast (> 6.25 cm per hour)	1
Moderate (2.0 – 6.25 cm per hour)	2
Moderately slow (0.5 - 2.0 cm per hour)	3
Slow (<0.5 cm per hour)	4
Land Use → Weight: 15.8	
Limestone area, paddy field, pine plantation	1
Shrub and bush, mixed garden, forest	2
Mixed paddy field with vegetable garden	3
Settlement, vegetable garden, sparse vegetation in forest region	4

3. RESULT AND DISCUSSION

3.1 Landslide Event in Study Area

Landslides often took place in the study area. A big landslide occurred on December 26th, 2007 in Ngledoksari Sub-Village, Tawangmangu Village. This event caused 34 victims and 105 damaged houses (Local Government of Karanganyar Regency, 2007) (see Figure 3a). Apart from that, there were 34 landslide locations found during the field work. Five of them are shown in Figure 3b-3f. Several landslides also occurred in remote area. Four locations of landslides were identified through visual interpretation of Ikonos image (2006) from Google Earth. The landslides are situated in landform of high hill in Sidoramping lava flow (*hhs*). This location is associated with very steep slope (more than 65%) and it is abandoned as sparse vegetated area.

Some landslide events cause damages and disruption in settlement area. The settlement areas are generally located in relatively steep area and in flat area surrounded by steep zone. The damages in settlement area encompass damaged houses and roads. Several damaged houses and roads in those locations can be still identified while the others are not. Most damaged houses due to landslide have been repaired. Almost all damaged roads have been also reconstructed.

Landslide type in study area is mainly rotational. This type has a unique characteristic in which the surface of rupture is curved upward (spoon-shaped) (Highland and Bobrowsky, 2008). Rainfall is the most triggering factor. A big landslide in Tawangmangu Sub District was primarily triggered by high rainfall intensity. The recorded daily rainfall intensity from five rainfall gauges on December 26th, 2007 tended to be the highest during the last 23 years. Total rainfall intensity in that day was approximately similar even higher than monthly rainfall intensity. The high rainfall intensity also caused other landslide events in the other villages.

The materials of landslide event in study area commonly consist of soil and rock. Soil is the dominant material. The domination of soil material appears as a consequence in terms of deep soil in the study area. On the other hand, landslide with rock material can be particularly identified in limestone hill.



Figure 3. Several Landslide Events in Study Area (a) in Tawangmangu Village, (b) in Kalisoro Village, (c) in Bandardawung Village, (d) in Tengklik Village, (e) in Karanglo Village, and (f) in Sepanjang Village

3.2 Landslide Susceptibility

Landslide susceptibility in this research is categorized into five classes utilizing natural breaks classification based on accumulative weight and score, i.e. very low (less than 221), low (221-263), moderate (264-298), high (299-328), and very high (more than 328). According to the established classification, most areas in Tawangmangu Sub District are prone to landslide. A half of study area is classified as high and very high susceptible zone. Moderate susceptible zone covers 36% of total area and it is only 14% of total area included as very low and low susceptible zone (Table 4). Spatial distribution of landslide susceptibility is shown in Figure 5.

Table 4. The Width Area of Each Landslide Susceptibility Class

Susceptibility Class	Width Area (Ha)	Susceptibility Class	Width Area (Ha)
Very Low	156	High	1,031
Low	828	Very High	2,457
Moderate	2,531	Total	7,003

In relation with actual landslide in study area, most of landslide events can be found in high susceptible (9 landslide events) and very high susceptible zone (22 landslide occurrences). Nevertheless, 8 landslide events occurred in the area classified as very low (3 events), low (1 event), and moderate susceptible zone (4 events).

3.2.1 Landslide Susceptible Zone

The very low susceptible area is situated in some parts of andecite hill (*adh*), middle part of small valley in Sidoramping lava flow (*svs*), and small part of Lawu lahar plain (*llp*) and lower slope of Mount Sidoramping (*lss*). This zone is utilized as paddy field, settlement area, and forest typified by moderately sloping (8 – 15%), moderately fast up to fast permeability, and clay loam-loam texture. The existing situations reduce the probability of landslide event in this area.

Low susceptible area exists in most areas of *adh*, *llp*, *svs*, and *lss*. Some areas in northern part of limestone hill (*lsh*) are also included in low susceptible zone. Low susceptible areas are mainly located in the slope of 0 – 30%. The land uses are settlement area, paddy field, vegetable garden (carrot, garlic, onion, and strawberry), mixed paddy field with vegetable garden, and forest. In addition, this area is also characterized by moderately slow up to fast permeability associated with clay loam and loam texture.

Moderate susceptible area is scattered in more than one third of Tawangmangu Sub District (36% of total area), particularly in high hill in Sidoramping lava flow (*hhs*), *llp*, and volcanic cone of Lawu Volcano (*vcl*) It is the dominant landslide susceptibility class in study area. The area is largely positioned in slope of more than 30%. Nevertheless, some areas in Lawu lahar plain are also included as moderate susceptible even though they have slope of less than 30%. In this case, broadly existence of settlement area and mixed paddy field with vegetable garden, slow permeability, and clay loam texture affects the probability of landslide event.

High susceptible areas are mostly located in low hill in volcanic rock formation (*lhv*), moderate hill in Sidoramping lava flow (*mhs*), and river valley (*rvt*). High susceptible areas generally take place in moderately steep up to steep area (more than 30%). Those areas are mainly used as settlement area, mixed garden, and vegetable garden. The intensive development of those land uses can be seen in steep zone. Also, the brittle parent material (Lawu volcanic rock) enhances the probability of landslide in this zone.

The highest susceptible areas are concentrated in northern part of study area. The areas pervade two landforms, i.e. *lhv*, *vcl*, eroded volcanic cone (*evc*), and front slope of Lawu Volcano (*fsl*). Some parts of *mhs* are also classified as very high susceptible zone. These areas are laid upon breakable parent material, i.e. Lawu volcanic rock. Moreover, very steep slope (more than 65%), the broad existence of mixed paddy field with vegetable garden, slow up to moderately slow permeability, and clay-clay loam texture bring the accumulation of the most driving factor of landslide in this area.

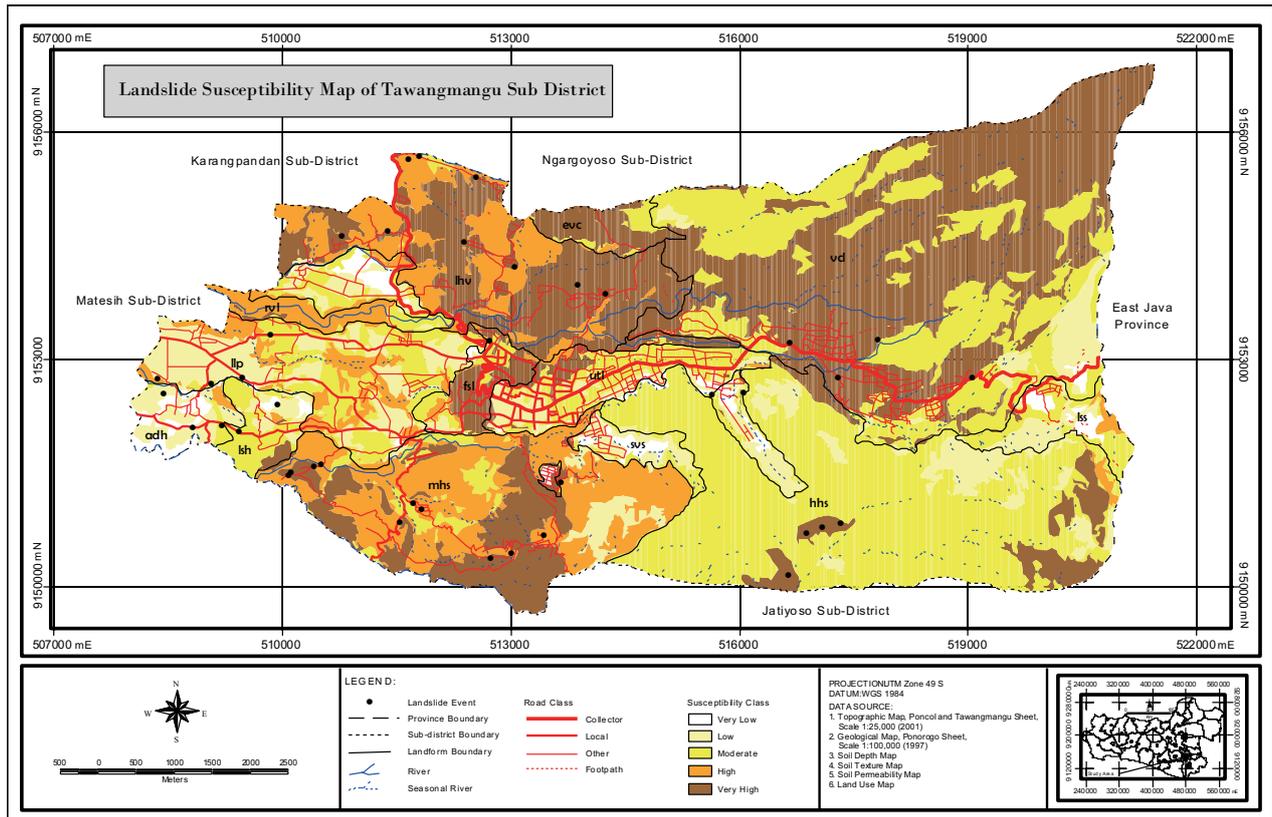


Figure 5. Landslide Susceptibility Map of Tawangmangu Sub-District

3.2.2 Settlement Area in Landslide Susceptible Zone

The development of settlement area increases rapidly. It is initiated by population pressure. The increasing number of population enlarges the demand of living space. The need of living place in Tawangmangu Sub District forces local community to harness every possible location for building their houses. Statistical data states that the width area of settlement area increases 4.65% within seven years. The width of settlement area in 2003 was 619.2 Ha (BPS, 2003) and it becomes 935 Ha in 2009 (Data Analysis, 2009).

Settlement areas in study area are broadly distributed from flat zone to steep zone. Local people mostly build their houses in relatively flat areas but those flat areas are sometimes surrounded by steep slope. It is found that many settlements areas are constructed in hill side or below the road. This circumstance reveals the risk related to landslide threat. It means that the development of settlement area sometimes does not take into account the hazard probability.

According to obtained landslide susceptibility map, it can be identified that there are many settlement areas are situated under landslide threat. More than one third of settlement areas (38%) are located in very high susceptible area. Moreover, 9% of settlement area (88 Ha) and 28% of settlement area (262 Ha) exist in high and moderate susceptible zone respectively. It is only 25% of settlement area located in very low and low susceptible zone.

The existence of settlement area in landslide prone area really needs the attention from local government. The number of vulnerable population due to landslide threat must be

considered. Local authority is suggested to array mitigation strategies for reducing the negative impact of landslide.

3.3 Landslide Mitigation Strategies

The number of actual landslide events in Tawangmangu Sub District shows that this area is relatively prone to landslide. Landslides have revealed disturbance and disruption for community in terms of damaged houses and casualties. To minimize the landslide impacts, local communities and related parties currently have conducted some activities in relation with landslide mitigation strategies, as follow:

- Constructed some warning signs in landslide prone area. Warning board is found at landslide location in Tengklik Village and at the edge of the road in Gondosuli Village.
- Constructed landslide early warning tool. This tool is connected to the land. The tool gives warning sign through loud siren when the land shakes. The tools are positioned in Ngledoksari Sub-Village, Tawangmangu Village and in Guyon Sub-Village, Tengklik Village. It is found that two of three warning tools in Ngledoksari Sub-Village are out of order which can be recognized from the broken string connection.
- Developed a landslide susceptibility map. This map is adhered in the office of Tengklik Village because the map is only made for Tengklik Village.
- Built retaining wall. The retaining wall is constructed for strengthening road construction in steep area. The retaining wall can be found in a new collector road connecting Karanganyar Regency and Magetan Regency. Some local roads are also invigorated by combining rock and cement.

- e. Disseminated information of landslide. The information consists of landslide hazard overview, evacuation planning, and landslide susceptibility map. The information compiled in landslide information board only exists in Tengklik Village.

The present landslide mitigation strategies are not sufficient. The existing landslide mitigation strategies are only locally conducted. It is not adequate regarding to the width of landslide prone area. Thus, the improvement and additional activities shall be performed. The proposed mitigation strategies are divided into two parts, strategies conducted by local government as the authority whether in regency, sub district, or village level and strategies executed by local community as possible affected people. The implementation process needs cooperation between community and government in order to create harmonious practice.

Local Government Strategies

- a. Develop detailed landslide susceptibility map particularly in scale of sub district. Local government can work together with academic institution for the expert assistance.
- b. Conduct regular landslide inventory to spatially recognize the distribution of landslide event by field checking or by visual interpretation of satellite imageries.
- c. Involve landslide information in spatial planning since landslide susceptibility zoning is used as basis information in controlling land allocation in landslide prone area.
- d. Construct and maintain landslide early warning system through cooperation among local government, local community, and other related parties. The number of the tools shall be also added due to the extensiveness of landslide prone area.
- e. Build strengthened structure in landslide prone area by applying the proper geo-technical method for road and building construction.
- f. Disseminate landslide susceptibility information to the lower authority and local community in order to increase the community awareness of landslide probability.
- g. Prepare evacuation planning to facilitate the evacuation session and distribution of social aid.

Local Community Strategies

- a. Recognize natural sign prior to landslide, for instance cracks in the land surface, prolonged heavy rain, and earthquake. After recognizing the landslide precursor, local community shall move in safer area.
- b. Avoid extensive land utilization in steep area in order to keep the slope stability. The assistance from the expert can be involved for guiding local community towards sustainable land use.
- c. Participate in maintaining landslide early warning system.
- d. Report landslide event to local authority to develop sufficient database of landslide.
- e. Cultivate several kinds of plants for strengthening the soil.

4. CONCLUSIONS

The research conveys some general findings, as follow:

- a. Landslide susceptibility information is particularly needed in landslide prone area. This information is also useful to recognize the exposed population and settlement area under landslide threat and to manage the land by allocating high susceptible zone as minor developed area or protected zone.
- b. Heuristic approach with weighted score method can be adapted or modified depending on the scale and purpose. The more specified data, particularly related to soil properties will give better result and precision.

REFERENCES

- Anbalagan, R and B. Singh, 2001. Landslide Hazard and Risk Mapping in the Himalayan. Paper in *Landslide Hazard Mitigation in the Hindu Kush-Himalayas* (ed.Li Tianchi, Suresh Raj Chalise, Bishal Nath Upreti). ICIMOD, Nepal.
- BPS (Center of Statistical Bureau) of Karanganyar Regency, 2003. *Kecamatan Tawangmangu Dalam Angka 2003*. BPS of Karanganyar Regency, Central Java.
- Fell, R, J. Corominas, C. Bonnard, L. Cascini, E. Leroi, W. Z. Savage, 2008. Guidelines for Landslide Susceptibility, Hazard, and Risk Zoning for Land Use Planning. *Engineering Geology* 102, pp. 85-98.
- Highland, L.M., and P. Bobrowsky, 2008. *The Landslide Handbook – A Guide to Understanding Landslides*. Geological Survey Circular 1325, Reston, Virginia, USA.
- Local Government of Karanganyar Regency, 2007. *Report of Natural Disaster and Aid Petition*. Local Government of Karanganyar Regency, Central Java.
- Smith, K., 2001. *Environmental Hazards: Assessing Risk and Reducing Disaster*. Third Edition, Routledge, London.
- United States Department of Agriculture (USDA), 1993. *Soil Survey Manual*. Soil Survey Division Staff, National Soil Survey Center, USA.