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Coseismic landslide susceptibility assessment using geographic information system

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Abstract

Background: Indonesia is one of the most earthquake prone countries in the world. More than 14,000 earthquakes of magnitude greater than 5 occurred in Indonesia between 1897 and 2009. Earthquakes are a major cause of slope instability eventually triggering coseismic landslides, which cost 1.5 million US$/ year in Java: one of the most densely islands in Indonesia. This paper aims to assess coseismic landslide susceptibility using Geographic Information System (GIS) on the western flank of Baturagung Escarpment, 8 km southeast of the Yogyakarta City, a data sparse area. Therefore, we have used a probabilistic seismic hazard analysis to calculate the peak ground accelerations, while the coseismic landslide susceptibility analysis was done by the scoring method in the GIS adopted from Mora and Vahrson model (Costa Rica), which is well adopted for data sparse areas.

Results: The west flank of Baturagung Escarpment is dominated by moderate level of coseismic landslide with an average Coseismic Landslide Susceptibility Level (CLSL) of 33–162. The upper slope of Baturagung Escarpment, which consists of Semilir Formation has the CLSL of 163–512, corresponding to medium level CLSL (Mora and Vahrson model). The low level CLSL is mainly located on the foot slopes of Baturagung Escarpment, while the alluvial and colluvial plains located along the Opak River have very low CLSL (0–6).

Conclusions: Based on the mapped landslide occurrence, the landslides tend to occur in the zone of moderate CLSL and they are distributed along the border between moderate and low coseismic landslide zone, meaning that the change on local condition could be playing an important role in triggering coseismic landslide.

Keywords: Coseismic landslide hazard, Geographic Information Systems (SIG)

Background

Indonesia is located at the junction among three active tectonic plates: the Eurasian Plate; the Indo-Australian Plate, and the Pacific Plate. The Indo-Australian Plate and the Pacific Plate are moving northward about 7.23 cm/year. (Demets et al. 1994) and westward about 11–12.5 cm/year. (Irsyam et al. 2010). Meanwhile, the Eurasian Plate is relatively constant. As a result, a giant fault known as Sunda megathrust was formed and extends approximately 5500 km from the north, running along the western side of Sumatra to the south of Java and Bali. This seismogenic structure is responsible for many great earthquakes in Indonesia. More than 14,000 earthquakes of magnitude greater than 5 (M > 5) had occurred over 1900–2009. Some of them had big impacts to the community such as Aceh earthquake in 2004 (Mw = 9.2); Nias earthquake in 2005 (Mw = 8.7); Yogyakarta earthquake in 2006 (Mw = 6.3); Tasikmalaya earthquake in 2009 (Mw = 7.4); Padang earthquake in 2009 (Mw = 7.6); and Kebumen earthquake in 2014 (Mw = 6.1) (Badan Geologi 2014).

Earthquakes can trigger secondary natural hazards, including landslides, rock falls, debris flows, barrier lakes and floods and tsunamis. Among all of those secondary hazards, coseismic landslides are the most widespread (Keefer 1994). In Java, one of the most densely islands in Indonesia, a thousand landslides were reported from 1990 to 2005 and caused damages that exceeded tens of thousands dollars (Hadmoko et al. 2010). The high intensity of rainfalls and the high seismic activities made Java as one of the most susceptible regions for coseismic landslides, especially in the southern mountainous areas.

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Both seismic and landslide hazards assessment have been well developed in Southern Yogyakarta. Some studies have identified the characteristics of the seismic and landslide hazards in Yogyakarta such as Walter et al. 2007; Wagner et al. 2007; Burton and Cole 2006; Burton et al. 2008; Haifani 2008; Sulaeman et al. 2008; Abidin et al. 2009a, b; Daryono 2011; Hartantyo and Brotopuspito 2012; Cahyaningtyas 2012; Karnawati et al. 2005; Hadmoko et al. 2010; Priyono 2012; Wacano and Hadmoko 2012; Nugroho et al. 2012. However, no studies about coseismic landslide susceptibility assessment have been conducted in this area.

On a worldwide scale, a coseismic landslide has attracted extensive attention among the scientists because the massive destructions that might occur. According to the Scopus database, at least eight international contributions use the word "coseismic landslide" in their title each year in the period 1990–2014 (Fig. 1). In Indonesia, the term of coseismic landslide is relatively new, since no coseismic landslide research and publication are found. Therefore, due to the physical conditions and the lack of coseismic landslide study, it is considered to conduct this study in order to provide a better understanding and information of coseismic landslide. This study aims to assess the coseismic landslide susceptibility by using Geographic Information System (GIS) on the western flank of Baturagung Escarpment, 8 Km southeast of the Yogyakarta City.

Two important kinds of approaches have been developed to model numerically earthquake-induced landslides, namely the deterministic and statistic approaches (Table 1). The deterministic approach includes the pseudo-static methods and is often referred to the Newmark-type or sliding block methods. It is a method that provides a proxy of slope stability based on stress variation due to the earthquake acceleration. Pseudo-static models have been significantly developed since Newmark (1965) introduced the sliding block method (Sarma 1975; Yegian et al. 1992; Kramer and Smith 1997; Bray et al. 1998; Bray and Rathje 2000; Saygili and Rathje 2008; Mehaan and Vahedifard 2013). The Newmark's method gives a detailed description of the performance of natural slopes during an earthquake. It also provides a reasonable prediction of slope displacement caused by an earthquake. However, the pseudo-static model highly simplifies and contains many assumptions that might not approximate the reality in various situations (Jibson 2007). Additionally, the pseudo-static model also has a number of difficulties to explain the spatial distribution of coseismic landslides.

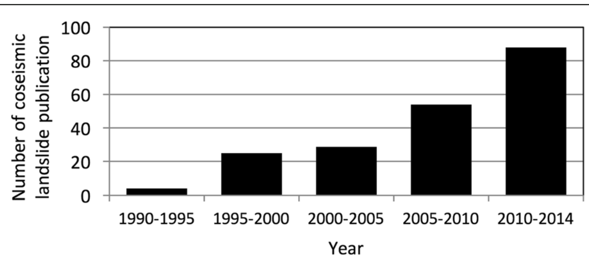

Fig. 1 Number of publications on coseismic landslides indexed in Scopus

Several statistical methods have also been proposed to evaluate and improve the Newmark's model. Some statistical analysis based on the Newmark's model result in a new equation and attenuation to assess coseismic landslide susceptibility (Romeo 2000; Jibson 2007; Jian et al. 2010; Rajabi et al. 2011). Other statistical methods based on the actual coseismic landslide occurrences have also been developed by Song et al. 2012 and Umar et al. 2014. Song et al. 2012 used the Bayesian network to describe the coseismic landslide, while Umar et al. 2014 used an integrated method of frequency ratio (FR) and logistic regression (LR) to define the most important factor in coseismic landslide occurrences. Since then, statistical method has become an alternative to model the coseismic landslide assessment, partly because of its flexibility of input data determination. The statistical method can describe the relationship among different combinations of instability factors. However, the statistical method gives indistinct results of spatial distribution of seismic characteristics (Huang et al. 2012) . In addition, the statistical method needs high accuracy data of coseismic landslide occurrences, which are not often available in Indonesia

The enhancement of remote sensing (RS) and geographic information system (GIS) technology have successfully answered this problem. With rapid computation capacities and relatively low cost, RS and GIS provide good platforms to model earthquake induced landslides (Wang et al. 2010). Several methods ranging from the simplest scoring and weighting calculation to a complex GIS model, either qualitative or quantitative analyses, have been developed to assess the coseismic landslide susceptibility. For instance, Khanzai and Sitar (2003) found that the highest abundance of the coseismic landslides occurred less than 40 km from the epicentre of the Chi-Chi earthquake. They found also that the ground motion was the most significant triggering factor of the coseismic landslides. Further improvements were brought by Miles and Keefer (2009) who successfully explained how to combine the Newmark displacement with fuzzy logic systems and GIS, while M.W. Huang, et al. (2012) gave a convincing explanation on how to integrate the geomorphic characteristics and ground motion attenuation. The coseismic model, which was produced by Wang et al. (2010), also successfully provided the basis information for the risk management and regional planning in Dujiangyan City, China. The model succeeded in generating a coseismic weight model that can be effectively used for coseismic landslide hazard and susceptibility assessment. In Indonesia (West Sumatra) Umar et al. (2014) analysed

Table 1 Summary of deterministic and statistical coseismic landslide models

Method	Model	Description	Reference
Deterministic	Newmark (Pseudo-static)	- calculates the coseismic landslide likelihood based on the dynamic stability of the slope and the earthquake ground motion. - appropriate for site specific coseismic landslide assessment and suitable for fairly stiff materials. - highly simplistic and contains many assumptions - Newmark's method treats a landslide as a rigid-plastic body	Newmark 1965; Sarma 1975; Yegian et al. 1992; Bray et al. 1998; Saygili and Rathje 2008
	Stress-deformation analysis	- based on the mathematical methods. - uses the finite-element model to estimate the strain potential at each node based on cyclic laboratory shear test of soil samples. - gives the most accurate explanation of slope behaviour during an earthquake - require high quality and sophisticated soil constitutive models - requires high quality and quantity of data - requires undisturbed soil samples and extensive laboratory analysis	Seed et al. 1973; Elgamal et al. 1990.
Statistic	Regression	- regression equations were generated using the data derived from the Newmark displacement model. - Needs extensive data on strong-motion and coseismic landslide occurrences - suitable only for large number of earthquake strong motion data and for rapid preliminary screening of sites.	Jibson 2007; Rajabi et al. 2011
	Integrated frequency ratio (FR) and logistic regression (LR)	- analyses various factors that might affect coseismic landslide - provides better explanation of relationship among the factors that might affect coseismic landslide - needs an extensive field survey and observation. - the results are sensitive to the data quality	Umar et al. 2014
	Attenuation model	- derives from the Newmark displacement model - needs extensive data on strong-motion and coseismic landslide occurrences. - Needs a data set of Newmark displacement	Romeo 2000; Jian et al. 2010
	Bayesian Network	- analyses various factors that might affect coseismic landslides - provides graphically and probabilistically of correlative and causal relationship among variables. - provides a natural way of handling missing data - can be easily combined with other analytic tools to aid management - difficult to treat continuous data - needs the accurate data on landslide occurrences	Song et al. 2012

earthquake induced a landslide by combining the statistical methods and GIS analysis to produce a rapid and accurate assessment for coseismic landslide disaster management and decision making. The results indicated that the prediction rates of the models made by peak ground acceleration (PGA) of 7.5, 8.6 and 9.0 were 79%, 78% and 81% respectively.

The methods of Umar et al. (2014) needs a large database of landslide occurrence to be effective but it provides the best results. For sparse data areas, the choice of methods knows a wider array of constraints. For such area, the Japanese Society of Soil Mechanics and Foundation Engineering created a manual in 1993. According to the manual, coseismic landslide assessment is classified into three categories based on their scale, namely; Grade 1, Grade 2 and Grade 3. Grade 1 refers to the lowest cost and most general level of zonation. It is based on the earthquake magnitude and seismic intensity. The rainfall pattern and geological condition are often used as an additional input data in this grade. Grade 1 is suitable for 1:1,000,000-1: 50,000 scale of mapping and suitable for preliminary analysis at the region or province level (Ishihara and Nakamura 1987; Keefer and Wilson 1989). In several cases, the zoning maps based on the Grade 1 category do not provide precise information for site-specific evaluation. Therefore, the zonation based on a Grade 2 assessment is required. Grade 2 zonation is based on the historical data of earthquakes, rainfall patterns, geological and topographical characteristics. It is suitable for a 1:100,000-1: 10,000 scale of mapping and often requires additional field investigations, remote sensing and aerial photo analysis (The Technical Committee for Earthquake Geotechnical Engineering, TC4 1993; Mora and

Vahrson 1999). A detailed level of zonation with large accuracy can be achieved by applying Grade 3. It combines the methods of Grades 1 and 2 with site specific investigation information to produce coseismic landslide zonation. Grade 3 is based on geotechnical investigation and suitable for a 1:25,000-1: 5000 scale of mapping (Newmark 1965; Wilson et al. 1979; Tanaka 1982; The Technical Committee for Earthquake Geotechnical Engineering, TC4 1993; Siyahi and Ansal 1999).

The integration of RS and GIS based on Grade 2 can generate a coseismic landslide model, which is well adapted for sparse data area, where field data acquisition is difficult. The application of this integrated method is very suitable for developing countries especially Indonesia due to their poor landslide data inventory and its physical condition.

Profile of study area

The study area is located 8 km southeast of Yogyakarta City. It covers of three regencies Gunungkidul (2.07%), Sleman (3.13%), and Bantul (94,80%). The total study area covers approximately 119.14 km^2 (Fig. 2). Located in the western flank of Baturagung Escarpment, the area also has various topographical conditions. The western part is flat with the lowest elevation of 7.96 m above sea level, while the eastern part is an undulating and very steep area with the highest elevation of 497.97 m above sea level (Fig. 3).

Like the other areas on Java, Baturagung's is characterized as a humid tropical climate with seasonal monsoonal rainfall. The maximum rainfall of monsoonal type occurs during September-February (Hamada et al. 2002). The highest average of annual rainfall between 1983 and 2003 was 1986 mm and the minimum average of annual rainfall (1983–2003) was 1081 mm. These high frequency and intensity of rainfall caused the western flank of Baturagung Escarpment susceptible to a high intensity of erosion and mass movement. Additionally, the foot slope and the upper slope of Baturagung area consist of relatively soft ancient volcanic rock.

The geology of the research area can be roughly divided into two major lithologies; ancient volcanic rock and alluvial deposits which cover the basement rock. These major lithologies can be subdivided into several smaller lithological units, namely, Alluvium (Qa), Young volcanic deposits of Merapi Volcano (Qmi), Nglanggaran Formation (Tmn), and Semilir Formation (Tmse). The Qa generally consists of gravel, sand, silt, and clay along the river, formed through the denudation processes on the steep and very steep areas. The Qmi consists of undifferentiated tuff, ash, breccia, agglomerate, and lava. It was formed through the sedimentation process of Merapi Volcano deposits transported by several big rivers such as Opak River. Both the Nglanggran Formation and the Semilir Formation were formed from an ancient

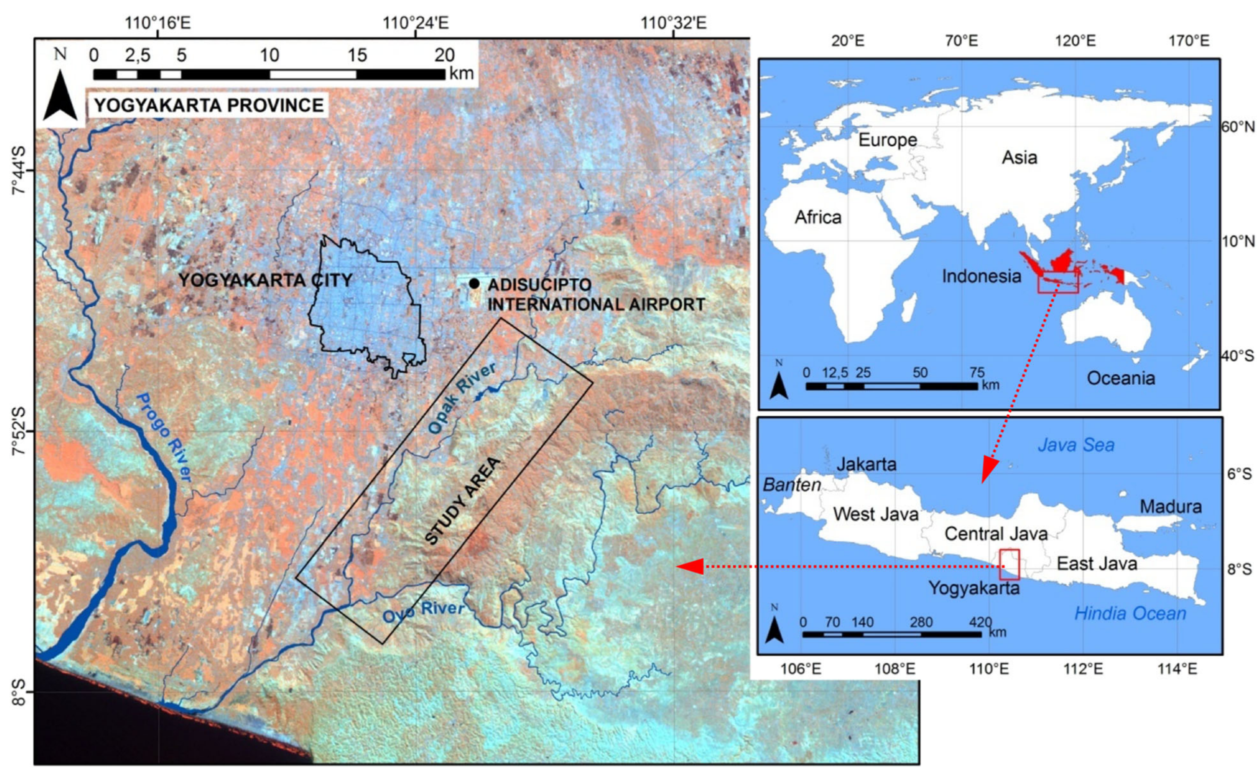

Fig. 2 Study area map (derived from ASTER imagery and Global ESRI data)

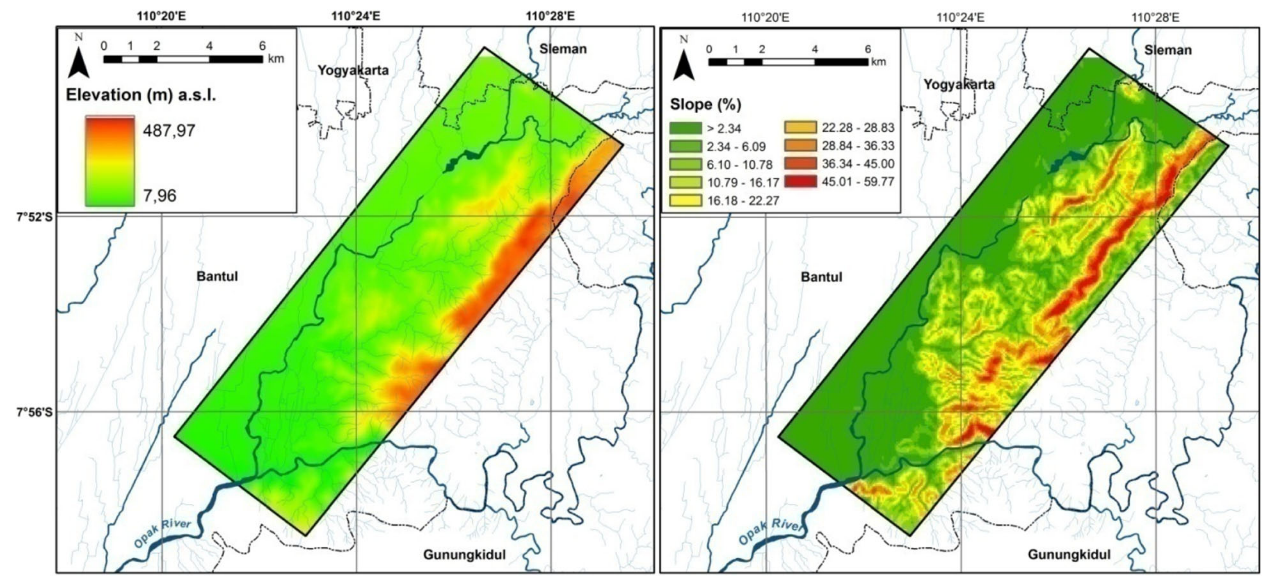

Fig. 3 Elevation map (*left*) Slope map of research area (*right*), DEM derived from the topographic map of Geospatial Information Agency of Indonesia

Volcano on the southern Yogyakarta Province. The Tmn was formed in the early Miocene and composed of volcanic breccia and lava flow containing breccia, agglomerate rock and tuff, while the Tmse was formed between the late Oligocene and early Miocene. Tmse consists of interbedded tuff-breccia, pumice breccia, dacite tuff and andesite tuff, and tuffaceous claystone (Fig. 4). There is a major normal fault oriented SW and NE known as Opak Fault which is closely related to the subduction process on the 250 km south part of Java. This major fault was responsible for the big earthquake that occurred at 27 May 2006 in Yogyakarta (Abidin et al. 2009a; Natawidjaja 2007).

Situated along the Baturagung Escarpment, the research area is dominated by three major groups of landforms originated from structural, fluvial, and denudation processes (Nurwihastuti et al. 2014) . The structural landform can be recognized from the topographical difference between the escarpment in the east and the sub horizontal area in the west of the research area. The intensive denudation processes occur on the middle slope and upper slope of the escarpment and also on the hilly areas of the Semilir Formation, which have less vegetation and utilized as dry land farming and traditional mining of breccia pumice. The fluvial landform containing alluvium is located along the Opak River in the western part of research area. The fluvial processes also take place in the narrow plains between the hilly areas in the east part of research area.

Methods

The method of Mora and Vahrson (1999) has been adopted in this study to generate coseismic landslide susceptibility zonation. The zonation was built for slopes failures in Costa Rica, which has heavy rainfall and high seismic activity, as Indonesia does. This model analyses two main factors of coseismic landslides: the factors that predispose coseismic landslide susceptibility and the factors that trigger coseismic landslide. The similarity of physical characteristic and the data availability make the Mora and Vahrson (1999) model applicable in the research area. Therefore, an integrated GIS and RS was conducted following the Mora and Vahrson's (1999) model. Raster-based GIS was used to analysis several parameters including relief condition, geology, humidity of the soil, seismic intensity, and rainfall intensity. The overlay and raster calculation in GIS were mostly used to generate the coseismic landslide susceptibility map. Figure 5 shows the flowchart of the coseismic landslide susceptibility assessment using GIS.

GIS analysis was used to generate a lithology index (Sl value) and a relief index (Sr value). The soil humidity index and the rainfall intensity index (Sh and Tp value) was derived from a Thiessen analysis in GIS. The Ts value was produced by calculating the PGA using Kanai attenuation (Douglas 2011). The Ts value was done through a mathematical analysis using Matlab software. Finally, all of the parameters were rasterized and analysed in GIS platform in order to generate a coseismic landslide susceptibility model (Fig. 5) and the summary of input data can be seen in Table 2.

Research parameters

This study used the coseismic landslide susceptibility factors such as relief, lithology, and soil moisture. Additionally, the seismicity and rainfall intensity was used also as the triggering factors because the study site has a high intensity of rainfall and is prone area to the

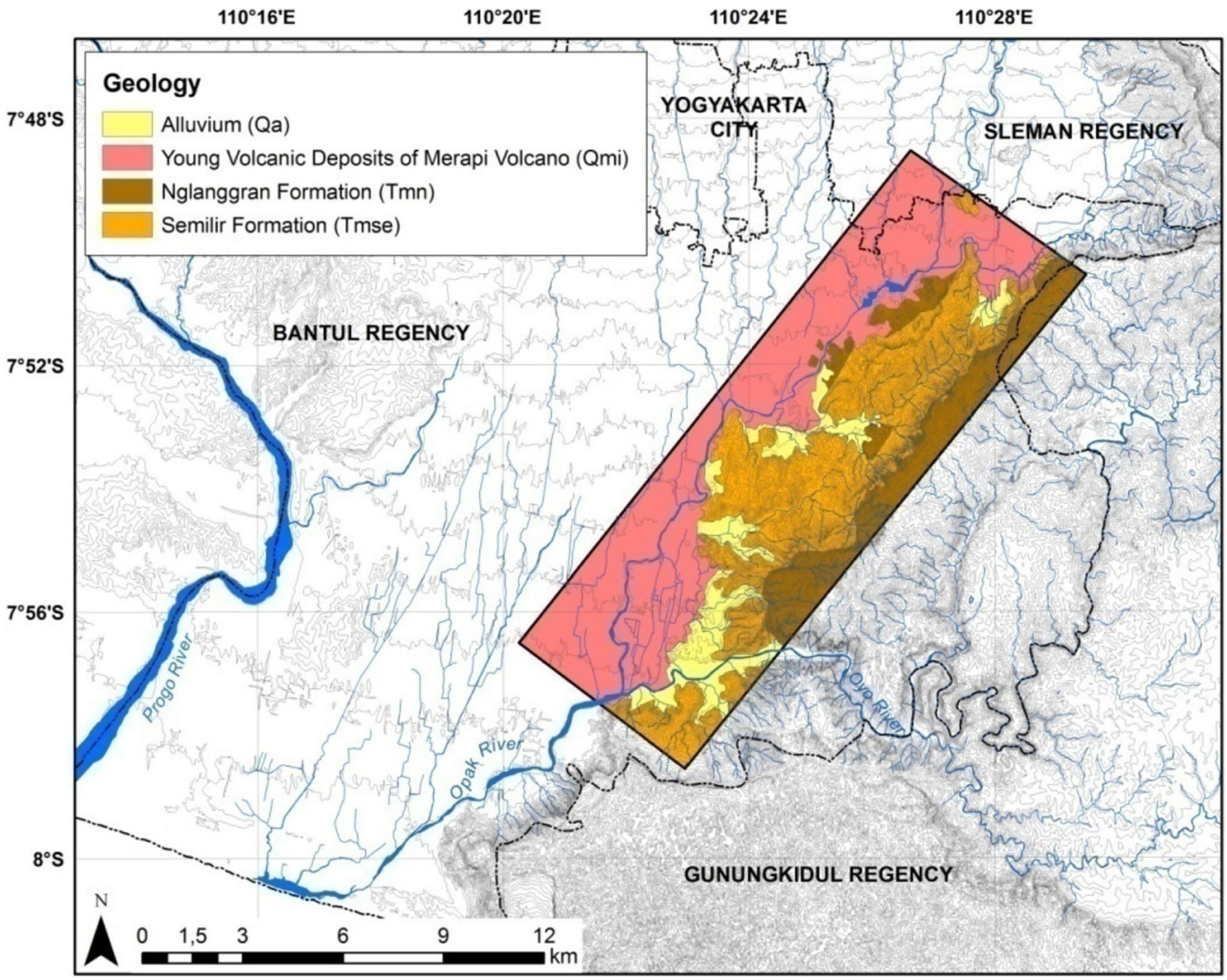

Fig. 4 Geology map of research area

earthquake. When the heavy rainfall occurs, the potential erosion is higher and the slope instability increases. As a results, the probability of coseismic landslide occurrence also increases. Therefore, by considering both seismic and rainfall intensity, the accurate susceptibility map can be produced. The detailed information of parameters used in this study are explained below.

Relief

The relief information was extracted from the existing topographical map (1:25,000) with 12.5 m contour intervals. The contour data was modified into slopes using Arc GIS software with 67.08 m of cell size and was converted into relief using classification shown in Table 3 below. Furthermore, the relief class was scored based on the Mora and Vahrson (1999) model (Table 5) to determine the relief index or Sr. The higher the topographical difference is, the higher the possibility of coseismic landslide occurrence. Therefore, the high relief difference was scored with 5 and the flat area (low relief class) was scored with 0.

Lithology

The lithological map was generated based on the 1:100,000 geological map of Yogyakarta (Rahardjo et al. 1995), the geomorphological map produced by Nurwihastuti (2008), and the visual interpretation results of ASTER imagery. The geomorphological map and the result of geological interpretation were used to control and improve the lithological information that was obtained from the geological map of Yogyakarta. The visual interpretation technique of ASTER colour composite of 3,4,PCA56789 was also used to obtain the information about the lithological feature in the research area. Three elements of visual interpretation namely colour or tone, texture, and pattern that was used to distinguish the lithological units. The lithology index (Ts) was obtained through the scoring process of the lithological classification

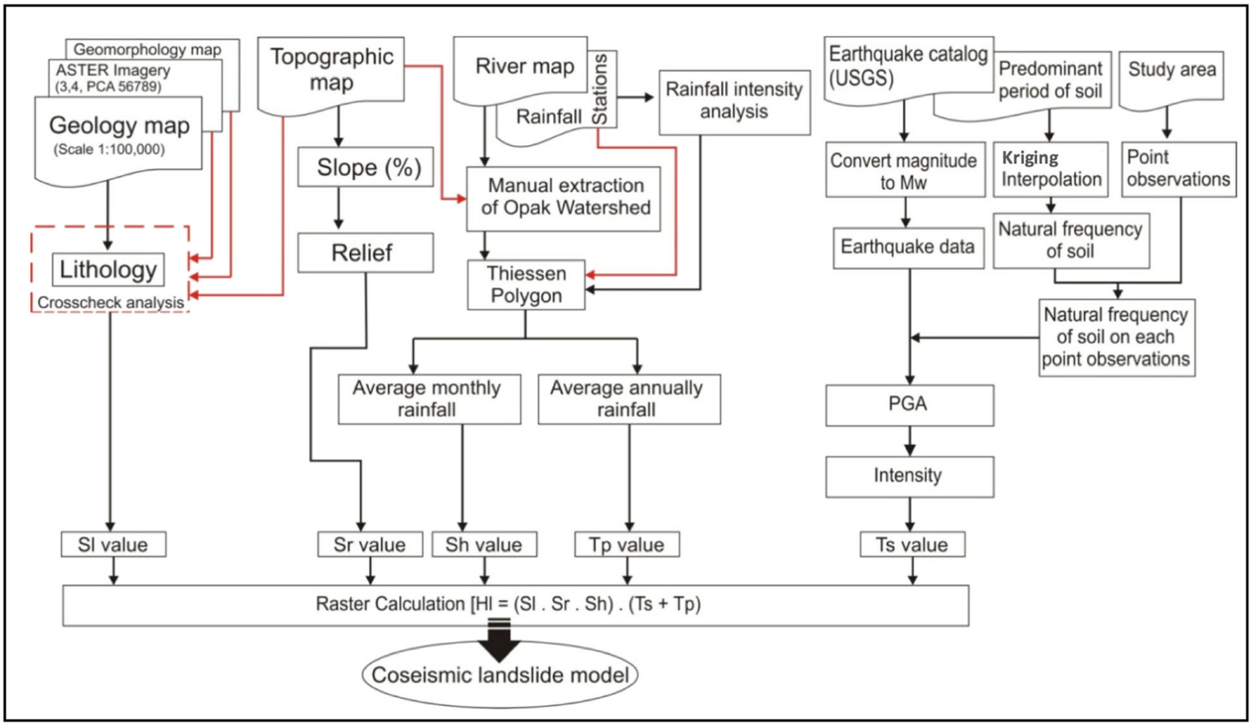

Fig. 5 Flowchart of coseismic landslide model

in Table 5. Soft sediment or rock and highly eroded rock is classified as a very high (5) susceptibility score, while the compact rock is scored as a low susceptibility score. In this case, the Semilir formation was scored higher than the other lithological units.

Natural humidity of soil

This study used the Thiessen polygon to divide the amount of rainfall in the study site in order to determine the natural humidity of the soil and the annual rainfall intensity. There were ten rainfall stations namely: Barongan, Dogongan, Jatingarang, Karangploso, Piring, Tanjungtirto, Terong, Umbulharjo, Wates and DPU Yogyakarta rainfall station. Most of them were located near the study area. The farthest rainfall station is Tanjungtirto which is located in 2.5 km north part of the study site (Fig. 6). The rainfall value in every Thiessen polygons was used to calculate the monthly average rainfall and annual average rainfall. The natural humidity index of the soil was derived from the scoring process of the monthly average of rainfall intensity. The area with the high average rainfall intensity (more than 250 mm per month) was determined as the highest (2) score of the monthly average rainfall intensity (Table 4). Finally, the natural humidity index (Sh) was obtained from the summation of the monthly average rainfall intensity score (Table 5). The maximum score of Sh was 24 while the minimum was 0. The area that has Sh value between 20 and 24 is considered as the area with the high intensity of rainfall and has the high natural humidity of soil which is very susceptible to landslide.

Afterwards, the summation of monthly rainfall score for 12 months was referred to as the natural humidity index of the soil. There were five categories of natural humidity index from very low humidity (0–4) and very high (20–24) used in the model (Table 6).

Earthquake intensity

The earthquake intensity was derived from the probabilistic seismic hazard analysis (PSHA) using 3481 earthquake occurrences with a magnitude greater than 5 Mw, which was obtained from the USGS catalogue between 1973 and 2014. The radius of 600 km from the centre of Yogyakarta City, lat.: -7.804082^0; long.: 110.364417^0, was applied to find the significant earthquakes that had affected the study area during the time period. The earthquake intensity was produced from the calculation of those all earthquake occurrences using the attenuation model proposed by Kanai (Eq. 1). This model was used because the equation includes the natural period of soil, which can amplify the ground motion during an earthquake. The natural period of soil (Tg)

Table 2 Description of the input data for the Mora and Vahrson (1999) model (Grade 2)

Parameters	Type	Description
Relief	Raster shape file (shp.)	▪ Derived from the slope analysis and contour data ▪ Contour interval: 12.5 m ▪ Scale 1:25,000 ▪ Published by Geospatial Information Agency of Indonesia
Lithology	Vector shape file (shp.)	▪ Derived from the 1:100,000 geology map of Yogyakarta (Rahardjo et al., 1995) and double-checked by topographic map, geomorphology map (Nurwihastuti, 2008), and visual interpretation result of ASTER imagery using 3,4, PCA56789 colour composite.
Natural humidity of Soil	Vector shape file (shp.)	▪ Derived from the rainfall data (1983–2013) of 10 rainfall stations in study area (Barongan, Dogongan, Jatingarang, Karangploso, Piring, Tanjungtirto, Terong, Umbulharjo, Wates and DPU Yogyakarta rainfall station) ▪ spatialized by Thiessen polygons
Seismic intensity	Raster shape file (shp.)	▪ Calculated from all of earthquakes occurrence with the magnitude greater than 5 between 1973 and 2014 obtained from USGS earthquake catalogue ▪ Attenuation used: Kanai attenuation model (Douglas 2011). ▪ Interpolation used: IDW method ▪ Using predominant frequency of soil from field measurement conducted by (Daryono, 2011).
Rainfall Intensity	Vector shape file (shp.)	▪ Derived from the rainfall data (1983–2013) of 10 rainfall stations in study area (Barongan, Dogongan, Jatingarang, Karangploso, Piring, Tanjungtirto, Terong, Umbulharjo, Wates and DPU Yogyakarta rainfall station) ▪ represented in Thiessen polygons

Table 3 The correlation between slope and relief (van Zuidam, 1986)

Slope (%)	Relief (m/km^2)	Classification
0–2	<5	Flat
2–7	5–25	Gently slope
7–15	25–75	Sloping
15–30	75–200	Moderately steep
30–70	200–500	Steep
70–140	500–1000	Very steep
>140	>1000	Extremely steep

was obtained from the previous field measurement conducted by Daryono (2011).

$$\boldsymbol{a} = \frac{\boldsymbol{a}1}{\sqrt{\boldsymbol{Tg}}} 10^{\boldsymbol{a}2\boldsymbol{M}-\boldsymbol{P}\log\, \boldsymbol{R}+\boldsymbol{Q}} \quad (1)$$

Where:
α is peak ground acceleration (PGA), a1 is constants value (5), a2 is constants value (0.61), Tg is the natural period of soil, M is the earthquake magnitude, R is the hypocentre (km), and P and Q are the values from Eqs. 2 and 3.

$$\mathbf{P} = \mathbf{1.66} + \left(\frac{3.6}{\boldsymbol{R}}\right) \quad (2)$$

$$\mathbf{Q} = \mathbf{0.167} + \left(\frac{1.83}{\boldsymbol{R}}\right) \quad (3)$$

The systematic sampling with 5.5 km^2 of grids over the study site was used to observed the PGA value by using the Eq. 1. At least, 319 observation points were involved in this study in order to determine the areal PGA of study area. The spatial interpolation was applied by using the PGA value of each observation points. Kriging interpolation (3 m of cell size) was applied in this analysis because Krigging calculates the prediction value based on the distance between the measured points, the prediction location and the overall spatial arrangement among the measured points. Finally, the PGA value of the study site was converted to the modified Mercalli intensity by using the following equation (Wald et al. 1999):

$$Imm = 3.66 \log(PGA) - 1.66 \quad (4)$$

The resulted intensity value from the Eq. 4 was scored by using the Mora and Vahrson (1999) model (Table 5) to generate the Ts index. The maximum Ts index of 10 was given to the intensity XII and the minimum Ts index of 1 was given to the intensity III. The higher the intensity of particular area was, the higher the ground motion occurred and consequently, it might affect the slope stability.

Annual rainfall intensity

Similar to the natural humidity index analysis, the annual rainfall intensity (Tp value) was generated by calculating the average annual rainfall in each Thiessen polygon for at least 10 years. There were five classes of average annual rainfall intensity (Tp) with the lowest class was very low (<50 mm) and the highest class was very high (>175 mm) (Table 5). The higher the value of Tp index was, the higher the susceptibility level of landslide occurrence.

Coseismic landslide susceptibility assessment

All parameters value described above were transferred into digital format using the Arc GIS software. The coseismic

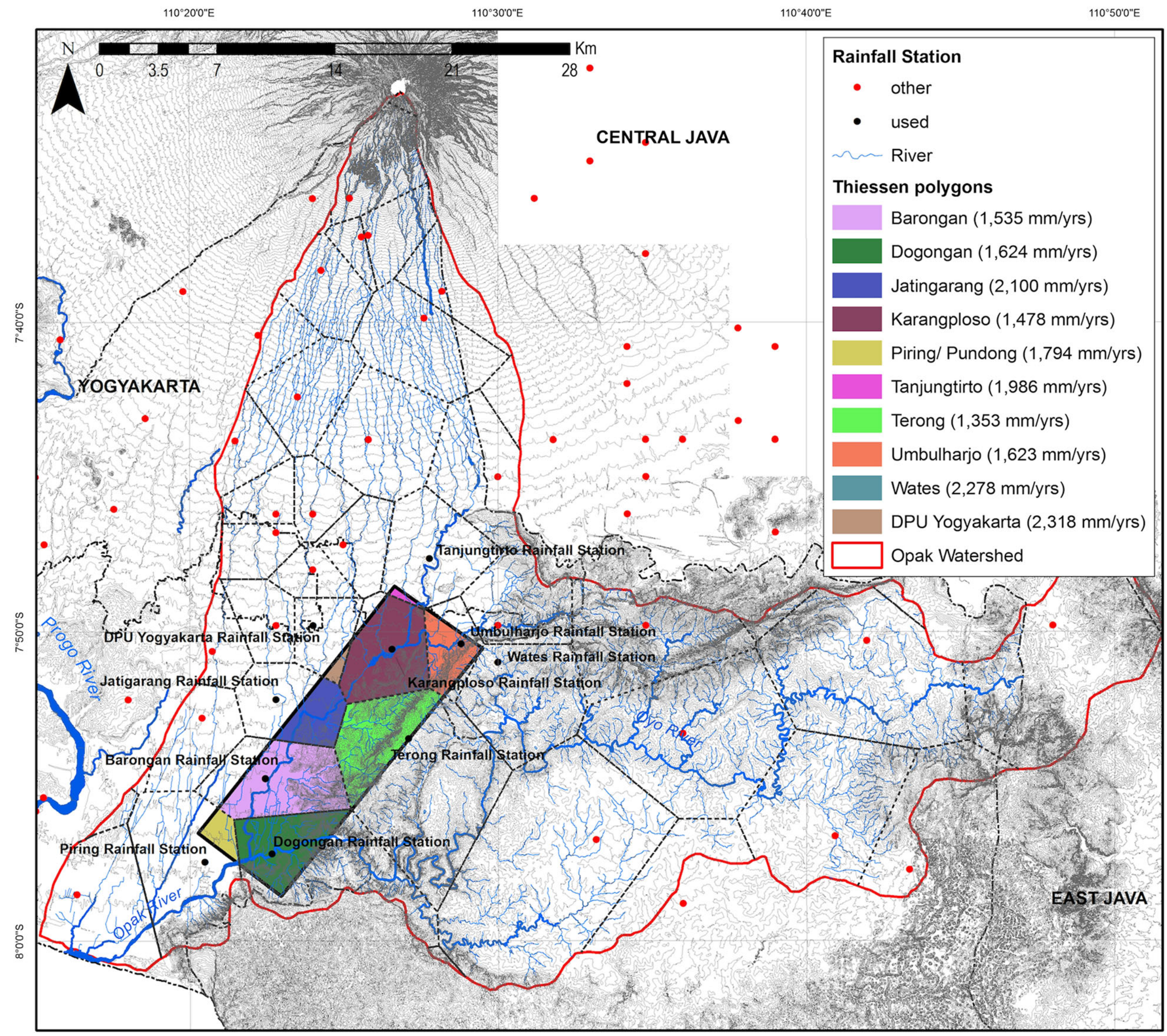

Fig. 6 The distribution of rainfall station used and the Thiessen polygon of study area

landslide susceptibility assessment was carried out through raster based analysis using the following equation:

$$landslide\ susceptibility = (Sr \cdot Sl \cdot Sh) \cdot (Ts + Tp) \qquad (5)$$

where, Sr is the relative relief index, $Sl_l$is the lithological susceptibility, Sh is the natural humidity of the soil, Ts is the seismic intensity, and Tp is the rainfall intensity. All the indexes of the input parameters were calculated by using the raster calculator with the output cell size was 67.08 m. Based on the Eq. 5, six categories of areas, i.e., negligible, low, moderate, medium, high, and very high was resulted. The minimum value of the coseismic landslide susceptibility index using the Eq. (4) was 0, while the maximum value was 1250 (Table 6).

Table 4 Average monthly of rainfall intensity classification in order to generate the natural humidity of soil

Average rainfall intensity	Score
<125 mm per month	0
125–250 mm per month	1
>250 mm per month	2

Results

In general, the maximum class of relief of the study area was the medium susceptibility class (301–500). This area is located on the middle to upper slope of western Batuargung Flank. About 792 pixels with the size of 67.08 m or approximate about 5.31 ha were defined as

Table 5 Parameters used in coseismic landslide susceptibility assessment

Parameters	Classes	Susceptibility	Score
Relief (m/km^2) (Sr)	0–75	Very Low	0
	76–175	Low	1
	176–300	Moderate	2
	301–500	Medium	3
	501–800	High	4
	>800	Very High	5
Lithology (Sl)	Permeable limestone, slightly fissured intrusions, basalt, andesite, granites, ignimbrite, gneiss, hornfels, low degree of weathering. Low water table, clean regose fractures, high shear strength rocks.	Low	1
	High degree of weathering of above mentioned lithologies and of hard massive clastic sedimentary rocks, low shear strength, shareable fractures	Moderate	2
	Considerably weathered sedimentary, intrusive, metamorphic, volcanic rocks, compacted sandy regolithic soils, considerable fracturing, fluctuating water tables, compacted colluvium and alluvium	Medium	3
	Considerably weathered, hydrothermally altered rocks of any kind, strongly fractured and fissured, clay filled, poorly compacted pyroclastic and fluvio-lacustrine soils, shallow water table.	High	4
	Extremely altered rocks, low shear resistance alluvial, colluvial and residual soils, shallow water tables.	Very high	5
Annual Precipitation (natural humidity index of soil) (Sh)	summation of average monthly rainfall		
	0–4	Very Low	1
	5–9	Low	2
	10–14	Medium	3
	15–19	High	4
	20–24	Very high	5
Intensities (MM) (Ts)	III	Slight	1
	IV	Very low	2
	V	Low	3
	VI	Moderate	4
	VII	Medium	5
	VIII	Considerable	6
	IX	Important	7
	X	Strong	8
	XI	Very Strong	9
	XII	Extremely Strong	10
Influence of rainfall intensity as a triggering factor for landslide (rainfall n < 10 Years; average (mm) (Tp)	<50	Very low	1
	51–90	Low	2
	91–130	Medium	3
	131–175	High	4
	>175	Very High	5

the susceptible area in term of relief condition. The low susceptible relief area is distributed on the centre part and west part of the research area (Fig. 7). In term of lithological susceptibility, the Semilir formation was considered as the medium susceptibility class and the Nglanggran Formation was defined as the moderate susceptibility class due to their types of rock, compactness, hardness, the levels of weathering and the levels of erosion. The Semilir formation become the most susceptible lithological unit in study area because it consists of relatively soft rock and also has a high level of weathering and erosion.

Based on the monthly average rainfall intensity, the study area was divided into two main zones of natural

Table 6 Coseismic Landslide Susceptibility Level (CLSL), as derived from Eq. 4

Value from Equation 4	Class	Susceptibility
0–6	I	Negligible
7–32	II	Low
33–162	III	Moderate
163–512	IV	Medium
513–1250	V	High
>1250	VI	Very high

soil humidity. The area was divided between low (class 2) and medium (class 3) natural humidity. The 'low class' of natural humidity is mainly located in the mountainous areas in the east part of study area, while the medium class is located in only a small part of the plain in the west part of study area. Regarding to the seismic intensity level, the maximum PGA (950 gal) is located southeast part of study area near the epicentre of the last Yogyakarta earthquake. The PGA value gradually declined in the west part of research areas. The lowest PGA was about 654 gal. Based on the intensity calculation by using the Eq. 4, the study site was defined into the intensity IX. The resulted map of scored parameters is shown in Fig. 7.

The research area was characterised as class I to IV on the CLSL and divided into 4 zones: negligible, low, moderate, and medium zones (Fig. 8). Negligible zones are the most stable and safe areas. These zones are usually located on the flat to gentle slope areas (0–8%). Most of them are associated with alluvial plain, colluviums-alluvium foot slope and natural levee. The alluvial plain contains undifferentiated volcanic rocks of Young Merapi Volcano, while the colluviums-alluvium plain contains bad sorted alluvium, known as colluviums as a result of sedimentation process of denudation material from the mountainous areas in the eastern area. Some other negligible zones are located on the summit of Baturagung escarpment which is the Nglanggran Formation. The total area of negligible zones was 71.18 km^2 (59.78%).

The low CLSL or class II is associated with the border areas between mountainous and flat areas in the eastern part. Most of them are located on sloping areas (8–15%) and very close to rivers. These areas include the lower slopes of strong eroded denudation hills of the Semilir Formation and residual hills of the Nglanggaran Formation. Although these zones are relatively stable and safe, building constructions should be avoided, because the landslide body is often deposited in the lower slopes areas. The total area of the low susceptibility zone was 4.02 km^2 (3.38%).

About 41.32 km^2 or 34.71% of the area was categorized as the moderate level of CLSL. This area is associated with the moderate to steep slope areas (15–30%). The moderate zones are mainly located on the middle slope of the strong and weak eroded denudation hills of Semilir Formation, which contains of interbedded tuff-breccia, pumice breccia, dacite tuff and andesite tuffs and tuffaceous claystone. The Semilir Formation is characterized as fractured weathered rocks with thin soil thickness due to the advance denudation process. The traditional mining of breccia pumice has created an extensive open area and caused the excessive erosion. According to the landslide occurrence map, most of landslides occurred in this zone (Fig. 8).

The medium of CLSL was about 2.25 km^2 (2.14%), mainly located on the steep or very steep slopes regions (>30%). This zone is often associated with the upper slope of the Baturagung Escarpment member of Semilir Formation. Human activities still can be found in these areas, although the areas have more than 30% of slope steepness. These zones are mainly used as dry fields or "*tegalan*". Additionally, there are several fresh water springs located in the medium zones. Landslides will eventually bring the worst impact to the local

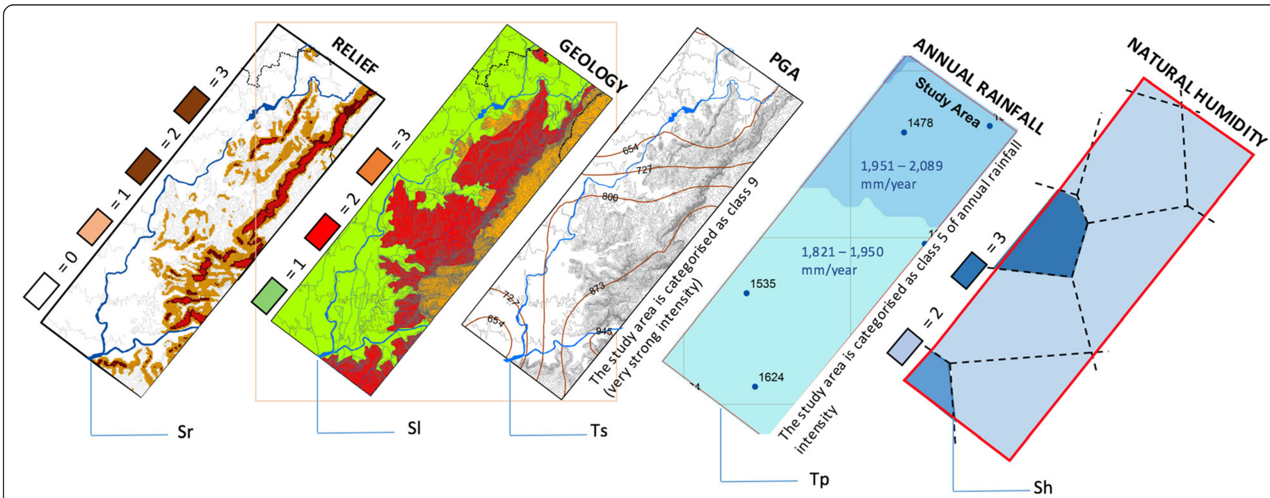

Fig. 7 All scored parameters

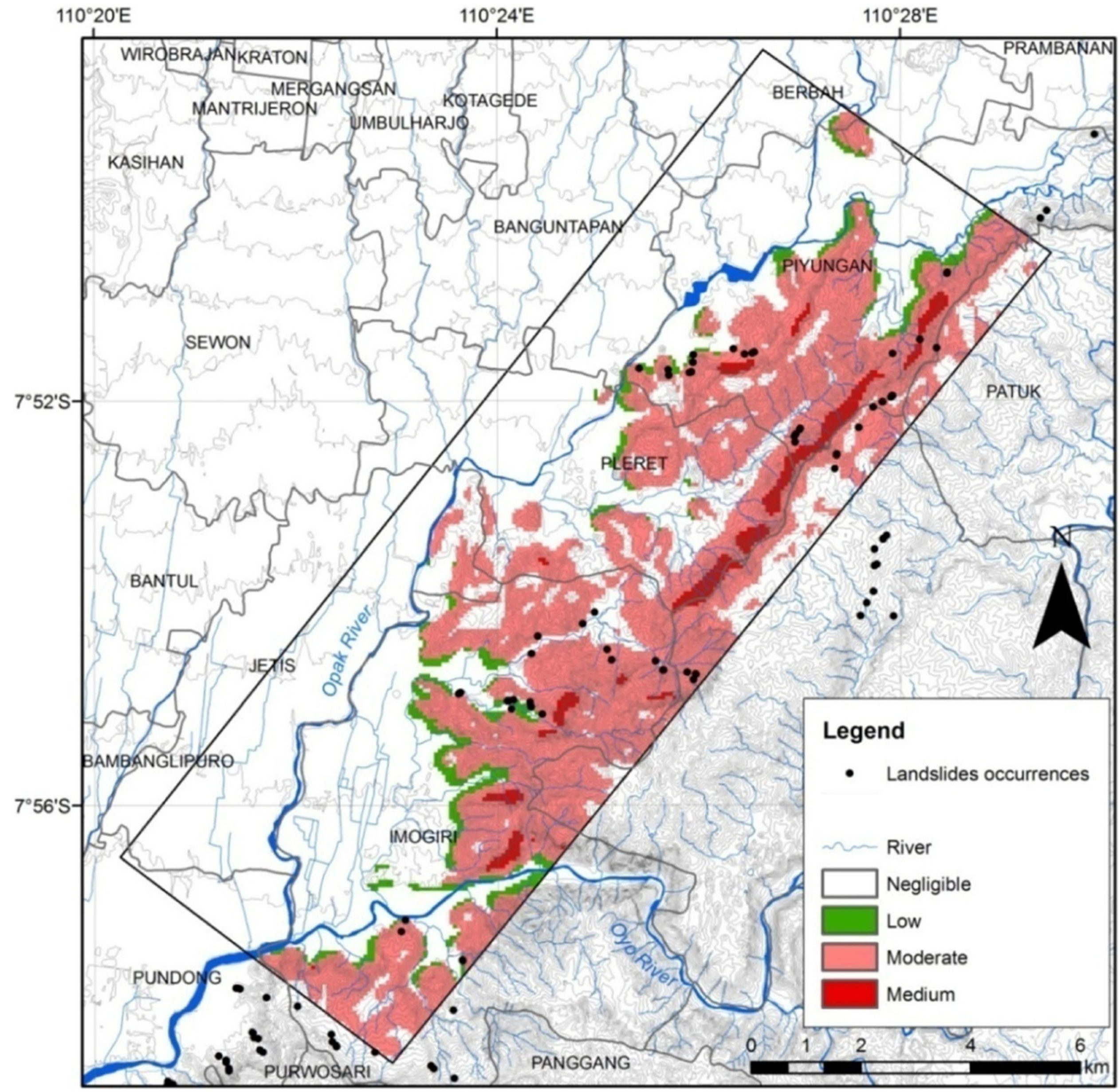

Fig. 8 Coseismic landslide hazard map based on Mora and Vahrson (1999) model

people, because they really depend on the fresh water springs to meet their daily water needs.

Administratively, three sub-districts were susceptible to coseismic landslides: Piyungan, Pleret, and Imogiri sub-district (Fig. 8). Piyungan had about 10.78 km^2 of moderate and 0.95 km^2 of medium CLSL zones. Due to its location, at least 37.04 ha of residential areas with 76 inhabitants per hectare (BPS 2012) are in danger in this sub-district (Fig. 9). The Pleret Sub-District had 11.38 km^2 of safe areas, 0.29 km^2 of low CLSL, 6.78 km2 of moderate CLSL, and 0.75 km^2 of medium CLSL. The medium and moderate CLSL zones are located in the eastern part of this sub-district, where about 38.95 ha of settlements are located close to medium susceptiblility zones. The average population density of Pleret sub-district is 74 people per ha. It means that more than 2000 people are living with the high coseismic landslide risk. About 63.36 ha of residential areas with 58 inhabitants per hectare are located close to susceptible areas to coseismic landslide occurrences in Imogiri sub district.

Discussion

According to the coseismic landslide susceptibility level (CLSL), about 59.78% of the total research area could be

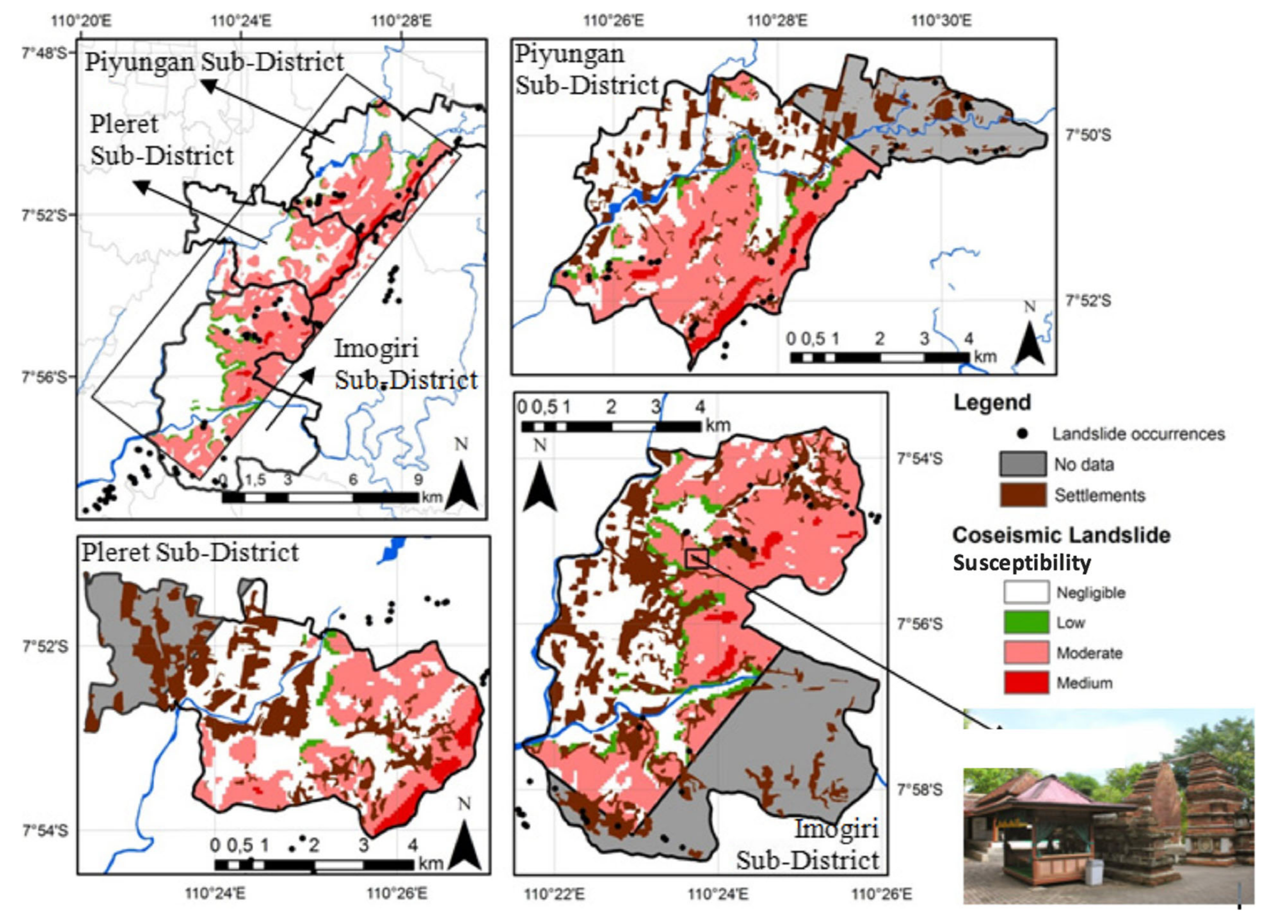

Fig. 9 The coseismic landslide zonation in Piyungan, Pleret, and Imogiri Sub-District

categorised as the stable and safe area. The CLSL level I is dominated by flat area consists of Young volcanic deposits of Merapi Volcano and Alluvium. This area also can be found on the summit of Baturagung Escarpment. The low CLSL (3.38%) is located in the border area between flat area and hilly areas consists of Semilir Formation and Nglanggran Formation. The moderate (34.71%) and the medium (2.14%) CLSL are located on the middle and upper slope. The middle slope consists of Semilir Formation, while the upper slope consists of Nglanggran Formation. The absence of good coseismic landslide and landslide data inventory in study area made the resulted CLSL model difficult to verify. However, by comparing the CLSL model with the only landslide data inventory available in the research area, it will give an illustration of the accuracy of the resulted model. Based on the landslide data, landslides tended to occur on the medium and moderate area of CLSL. Most of them occurred on the middle to upper slope. This area consists of Semilir Formation which is located on the several main faults. Opak fault is located in the west part of the Semilir Formation and there are also two main strike-slip faults that trimmed this formation namely Punthuk-Bawuran-Cinomati Fault. This fault is located between Segoroyoso-Bawuran Villages. The other fault is Becucu-Tekek Fault which is located in the north part of research area. Both of them have west–east orientation. Because of this condition, there are a lot of joint that can be found in the Semilir outcrop. Additionally, most of the Semilir hilly areas have the sun facing aspect which can increase the weathering level of Semilir Rock. The heavy rainfall and less vegetation cover create also the higher level of the weathering and erosion processes. That why, the landslides occurrences distributed mainly in the middle to upper area of Semilir Formation. The contact lithic between Semilir and Nglanggran Formation that located in the upper area Baturagung Escarpment has the higher landslide occurrence (Fig. 10). Similar to the Mora and Vahrson (1999), in general the CLSL model show a good correlation between the distribution of landslides data inventory and areas that has a higher degree of susceptibility (Fig. 10). It indicates that the methodology and the results are acceptable and reliable. However, further study that focuses on the

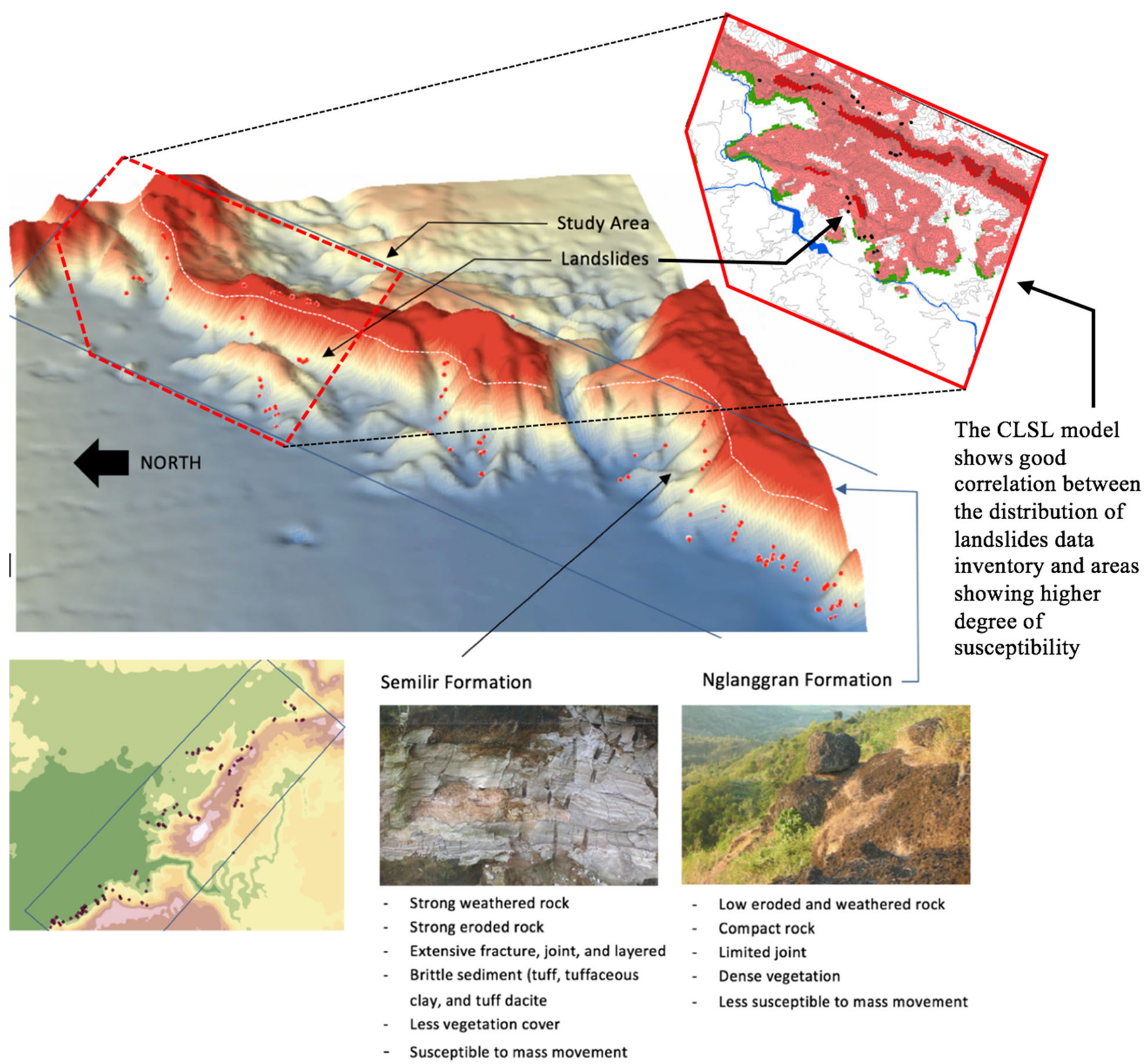

Fig. 10 Pattern of landslide distribution along the Baturagung Escarpment. The interpretation of the results shows a clear overlap between the middle slope and a lithological change (Semilir and Nglanggran Formation)

justification of the model by using better landslide or coseismic landslide data inventory is recommended.

Additionally, the results of this study are in line with other landslide research in the west of Yogyakarta (Priyono et al. 2011; Samodra et al. 2016). They also found that the level of landslide occurrence was high on the middle slopes. Priyono, et al. (2011) found that the high level of landslide vulnerability was characterised as middle to upper slope area with steep to very steep slopes (>60%), which displayed a high level of weathering and erosion. These results were also corroborated by the trajectory analysis of rock falls data inventory conducted by Samodra et al. (2016). They found that the most of potentially rock falls were triggered from the middle slope. Moreover, the middle slope also produced the most dangerous rock falls for homes located nearby, because it generateed some of the highest velocity of rock falls (Samodra, et al., 2016)

The CLSL result provideed important information in coseismic landslide susceptibility zoning. The unavailability of coseismic landslide, landslide data and the difficulties to investigate the coseismic source directly were the main problems in this study area. Therefore, this information can be used as a basic information for local government to protect the residential house and important asset against the coseismic landslide. For instance, the royal cemetery complex in Imogiri. The Imogiri Sub-District is special sub-districts for Yogyakarta Royal circles, because the royal cemetery is located in this sub-district. This area is very valuable for the cultural heritage of Yogyakarta. Until today, many pilgrims from both local and international locations visit the royal cemetery during holidays or particular religious' events. In 2011, at least 635 of international tourists and 20,290 local tourists visited the royal cemetery (Dinas Pariwisata DIY, 2011). The complex is located in Girirejo, Bantul regency. it was built in 1632 by Sultan Agung, the King of Mataram Kingdom. Situated on the slope of Baturagung Escarpment, this area is prone to landslide and coseismic landslide (Fig. 9). The complex is located in moderate zones of CLSL which is very close to the nearest medium CLSL about 1.5 km downslope. It will likely become very high risk area, if an earthquake occurred.

Conclusion

The results prove that the proposed method can provide a better description of coseismic landslides spatial distribution. Based on the model, there are four distinctive CLSL: negligible, low, moderate, and medium zones. The negligible zone of CLSL are defined as the most stable and safe areas, which have value range between 0 and 6. These zones are usually located on flat—gentle slope areas (0–8%). Most of them are associated with an alluvial plain, colluvium-alluvium foot slopes and natural levees. The low zones of CLSL are associated with the border areas between mountainous and flat areas in the eastern research area. Most of them are located on sloping areas (8–15%) and very close to rivers. The moderate zones of CLSL are mainly located on the middle slope of the strong and weak eroded denudation hills of the Semilir Formation, which consists of interbedded tuff-breccia, pumice breccia, dacite tuff and andesite tuffs and tuffaceous claystone. The medium zones of CLSL is defined as the most unstable and susceptible to coseismic landslides in the study area. These zones are often associated with the upper slope of the Baturagung Escarpment, which are mainly located on the steep to very steep slopes (>30%). There is still a need improvement for further, which focus on the coseismic landslide data inventory and statistical analysis of coseismic landslide in order to obtain the better results of coseismic landslides hazard zonation.

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Authors' contribution
AS and CG collected the data, AS carried out the analysis of coseismic landslide, CG support on interpretation of the results. AS drafted the manuscript, CG, DSH and JS revised the manuscript. All the authors drafted, read and approved the final manuscript.

Competing interests
The authors declare that they have no competing interests.

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