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Compilation of Parameter Control for Mapping the Potential Landslide Areas

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Abstract

Batu Tourism City is located in a mountainous area, so based on information from the BNPB, it has quite a large potential for landslides. Landslide hazards can frequently disrupt public traffic due to road cuts. Landslide mapping digitally will contribute to handling and mitigation activities since the database can be updated in real time to anticipate landslide hazards. This study aims to map landslide-prone areas located in the Payung zone, Songgokerto Village, and Batu City. Landslide areas can be determined by mapping analysis using GIS software. GIS can determine the classification level for a landslide susceptible area. Some input data that will influence landslides, such as rainfall, wind, earthquakes, etc., was collected as the control parameters. All parts of the study area could be classified as areas with minor, medium, and major potential for landslides. Primary data are collected from geo-surveying (aerial images) using drone devices for interpretation of landslide susceptibility areas, geophysical to identify the type of soil or rock layers that completed their behavior, and slip planes as well using geo-electric, geotechnical engineering to predict slope stability with the correlation from cone penetration test (CPT) data, and geo-hydraulic to observe the rainfall and the catchment area model using the available secondary data. Geometrically, measurement data found that the average slope angle at the upper and lower of the East Java Province highway is around 40–50°. Studies from geophysical data identified that the hilly terrain in the object study area has been dominated by the weathered rock layer. Geotechnical data obtained shows the soil layers at the slope location will be stable with the water content under 35% during the dry season and may become unstable with the water content reaching over 50% due to the increase in saturation during the rainy season. The landslide that occurred was more caused by seepage behavior from surface water flow towards the sloping plane, and then the safety factor during the rainy season reached the critical values at SF = 0.58. During the dry season, the unsaturated process due to the temperature change generates a safety factor (SF) of more than 1.2. The compilation data produced maps of susceptible landslides and surface flow distribution.

Keywords: Parameter Data Collection, Quantitative & Quantitative Analysis, Surface Flow Distribution, Susceptible Landslide Mapping.

1. Introduction

People and researchers often mention landslides as one of the most harmful natural hazards. Landslides cannot be prevented, certainly, but some efforts can be created to minimize the occurrence of hazards in landslide susceptible

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areas. Now, the existence of digital mapping for potential landslide areas can help minimize the disadvantages caused by the generated hazards. The first time GIS (Geographic Information System) was introduced in the 1960s, it was only used for solving problems geographically using spatial analysis. Currently, the technologically advanced and widely used application GIS can produce a landslide digital map of a certain area with the highest accuracy. The occurrence of a landslide can be monitored and evaluated time by time to avoid a victim or traffic accident due to a landslide. The digital map of landslide potential can be updated from time to time to provide some information needed by the public and related national or local institutions or agencies. GIS can involve all factors that generate landslides systematically through all tools available [1]. In recent years, many researchers have discussed landslides using Geographic Informatics System (GIS) in the creation of a digital map for landslide map from many different perspectives [2]. The digital map for landslides can be approached by GIS using quantitative and qualitative methods [3]. And, both methods for solving a problem in the application of GIS are very independent, making it hard to avoid the subjectivity aspects from the operator, researcher, or engineer. Although the qualitative and quantitative methods have different points of view [4], the advanced technology of the GIS can also be capable to combine synergistically the qualitative and quantitative methods rapidly [5].

However, regardless of the capabilities of GIS through spatial analysis, the results are very dependent on the compilation of parameter controls for mapping the potential landslide areas as the input data. Many cases were addressed to the problem of landslides and did not consider other related disciplines or subjects, so that the assessment of landslides in a certain susceptible area was different from reality. In the case of the landslide in KWB (Batu Tourism City), the map for potential landslides in KWB produced by the local government (Batu City) using spatial analysis with a GIS application was only based on the coordinate point of landslide occurrence within a certain time. The map for the potential landslide is updated every year without consideration of a detailed analysis of geomatical, geophysical, geotechnical, and geo-hydraulic aspects before spatial analysis with the application of GIS.

KWB is in a mountainous area, including the Mountain of Panderman (2045 m height), the Mountain of Welirang (3156 m height), and the Mountain of Arjuno (3339 m height), and is designated by the BNPB (National Agency for Disaster Countermeasure) as a susceptible area to landslides. Secondary data and some observations in the field indicate that the landslide in KWB was generated qualitatively by human activities in the plantation, agriculture, or tourism areas, as well as some mistakes in the reforestation program. Quantitatively, these are due to the change in land cover or land use, the slope with susceptible erosion, the age of rock structure, the alteration of the physical properties of soil, the amount of rainfall, the duration of heavy rainfall, and massively strong winds due to climate change. Even the previous assumptions from some observations stated that most types of landslides occurring at KWB are a combination of flowing, sliding, and falling material (soil or rock) to the slope area. However, there was no assessment in the detail analysis in terms of geomatical, geophysical, geotechnical, or geo-hydraulic to support these assumptions.

This paper focused on the Payung zone, one of the susceptible landslide areas at KWB. The selection of the Payung zone was based on the frequency and occurrence level of landslides every year, especially during the rainy season. In this area, there is highway traffic between Kota Batu and the cities in the western part of East Java Province, such as Kediri, Jombang, etc. The highway traffic is very busy and serves twenty-four hours every day. This highway should not be closed when the incident of a landslide can be predicted previously. At the Payung zone, Songgokerto Village, and Batu City, the soil and/or rock layers move toward the hillside, and the landslide material will close the traffic access at the East Java province highway heading to the outside and into the KWB. The previous assumption must be supported by qualitative and quantitative evidence as the input data. Furthermore, this paper will discuss the collection parameter control for mapping the potential landslide area supported by geomatical, geophysical, geotechnical, and geo-hydraulic studies data. Then, a simple scheme of data compiled can create the digital map of landslide potential at Payung zone, Songgokerto Village, and Batu city based on the facts or data obtained from these studies and be easy to update time by time.

2. Research Methodology

2.1. Study Area

KWB is one of the most famous tourist cities in East Java and one of the cities that produce the largest apple fruit in Indonesia. The study area is one part of KWB and one of the places frequented by tourists; they called it the Payung area. Payung area is located at 112°29'16.05" - 112° 29' 39.48" EL and -7° 51' 35.52", -7° 52' 10.27" SL. Payung Zone has been regulated in Local Regulation No. 16 of 2012 concerning the administrative district border of Malang and KWB. Payung area has an area of around 100 hectares (ha) and exists at an altitude of 1000 to 1200 m above mean sea level (MSL). Figure 1 shows the location of the Payung area at KWB (marked by the brown color) [6]. Recently, KWB has been visited by local and foreign tourists in very large numbers every year. A tourist city should have an adequate level of safety and comfort for all visitors.

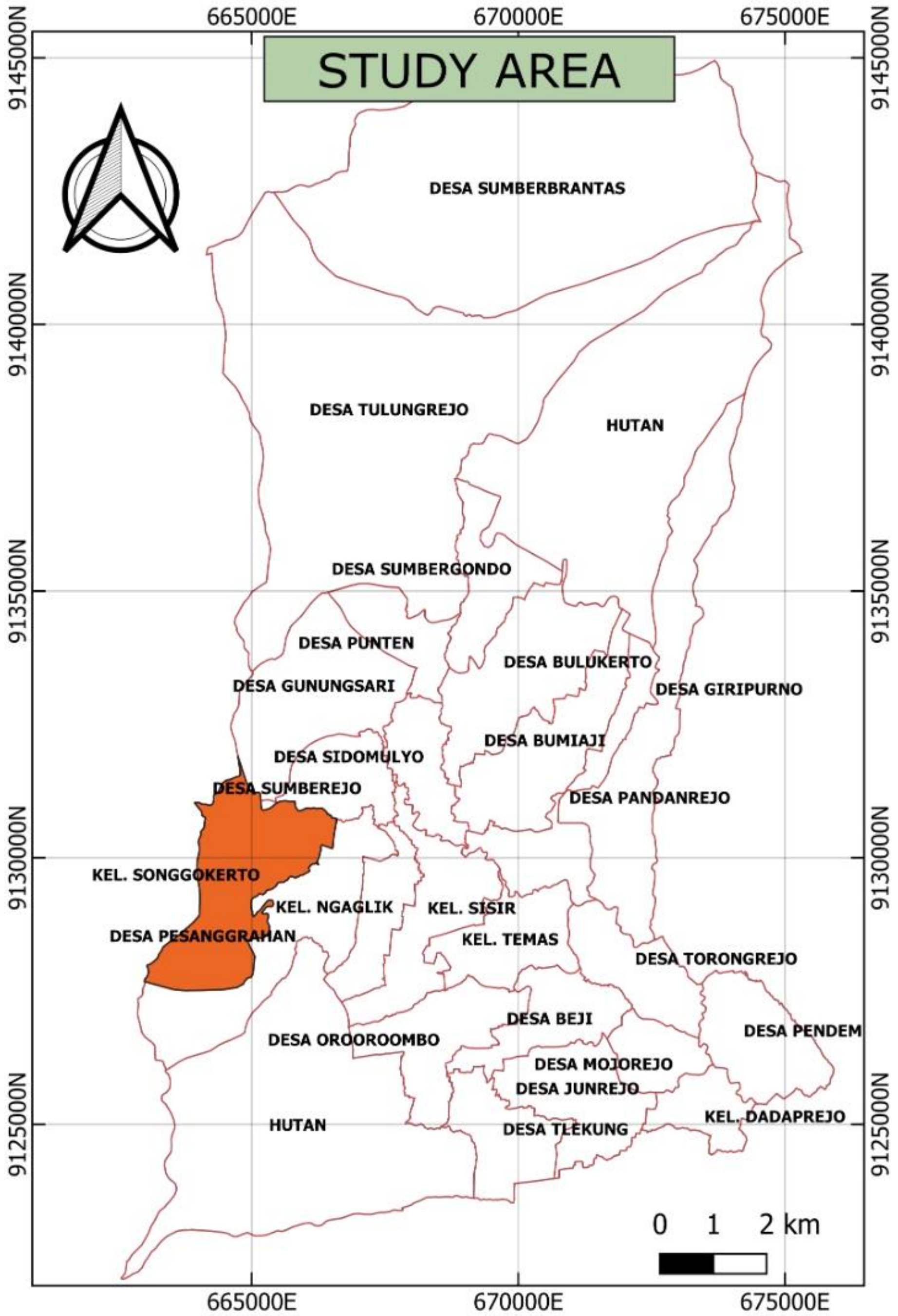


Figure 1. Map of KWB Administration.

2.2. Compilation of Parameter Control Data

Primary data is prepared for detailed analysis from geo-surveying, geophysical, geotechnical, and geo-hydraulic points of view. Primary data are collected from geo-surveying or geomatical data (aerial images or photography from air) using a drone device (Phantom 4 Pro V2.0 – DJI type) to assess the land covering or land use, the slope with susceptible erosion, and the result of this method was not only used to find all coordinates in the study area, but also this method could determine all position of CPT device and geo-electric instrumentation as shown as Figure 2, geophysical to identify the age of rock structure, type of soil or rock layers completed their behavior, and slip planes as well using geo-electric, geotechnical engineering to predict the alteration of physical properties of soil and the slope stability with using the correlation data from cone penetration test (CPT) data, geo-hydraulic to observe the time duration of heavy rainfall and the catchment area model using the Meteorological, Climatological and Geophysical data from BMKG Karangploso local office. The geochemical method will not be discussed in this study.

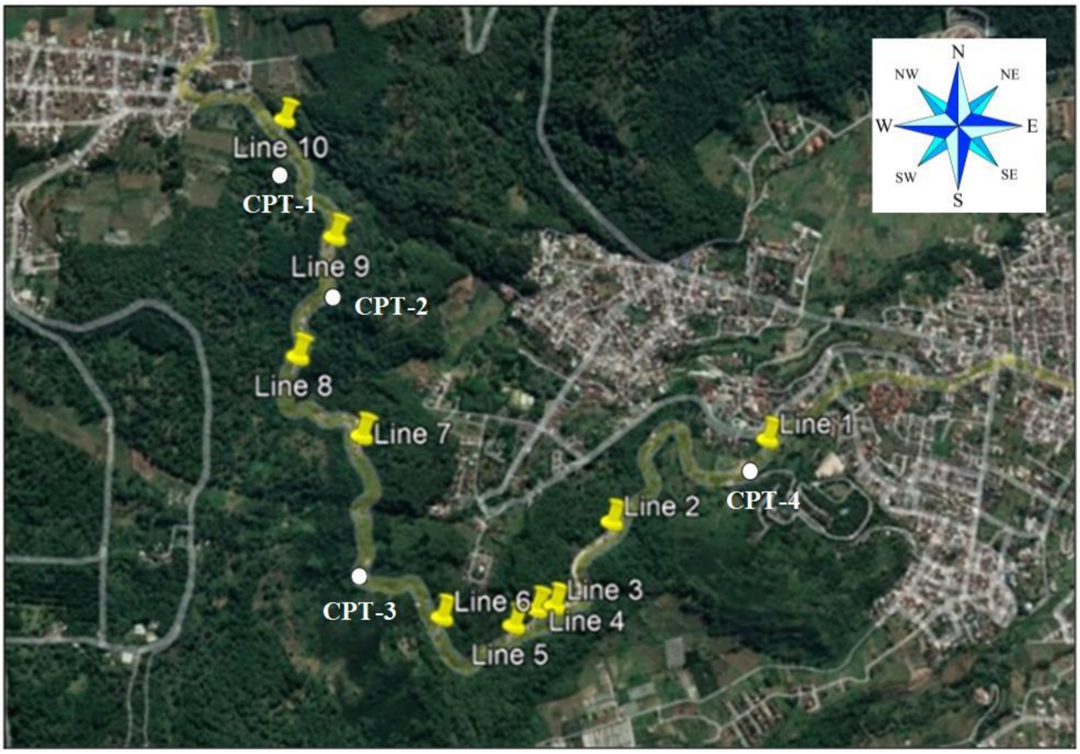


Figure 2. Field survey plan of geophysical (geoelectric instrument) and geotechnical (CPT devices) (Payung zone, Songgokerto Village, Batu city)

Figure 2 shows the field survey plan that will be performed at Payung Zone, Songgokerto Village. Geological measurements of geoelectricity were conducted by Schlumberger configuration. This method purposed to find some information vertically in soil or rock layers at the ground surface. The measurement points are at 10 locations along the Highway at Payung Zone in the direction from Jambuluwuk to the border gate of Batu City-Malang Regency. Data is displayed in 2-dimensional form by combining at least two Schlumberger measurement points [7]. The geotechnical investigation used a field test where cone penetration test methods were performed at 4 (four) points along this highway from the opposite direction. All field tests were implemented at the Payung zone during dry season conditions with little rain. The traffic condition was normal condition, there was no traffic jam. Traffic consisted of heavy vehicles (buses and trucks), small vehicles (sedans, family vehicles, etc.), and motorcycles.

2.3. Methods

The measurement of topography and slope gradient in determining the existing landslide distribution in the study area is important for the identification of landslides [8]. In this study, landslide locations were determined from the analysis of geomatical images, as shown in Figure 2.

Based on Figure 3, the methodology structure in this study is divided into three phases. The first phase is the acquisition of required data, including geomatical, geophysical, geotechnical, and geohydrological. The second phase consists of geo-surveying or geomatical analysis results that will be used to find out all the cross-sections of ground surface in lateral and longitudinal directions and to obtain some basin areas that have the potential to collect water surface and create the highest pore water pressure. Geophysical analyses can also determine the age and type of soil and rock layers, their behavior (weathered or not weathered) during loading or unloading by the water flow, the slip plane in soil and rock layers, the fluctuation of ground water table elevation, and ground water flow pattern during dry and rainy seasons [9]. Geotechnical engineering can observe all cross-sections to determine the areas that have landslide potential based on the safety factor (SF) computer-based system for simulation analyses, geo-hydrological can analyze flow patterns above and below the ground surface (laminar or turbulence), and geo-hydrological can also find the catchment area model that will be suitable for landslide areas, especially during the longest duration of precipitation or rainfall.

Secondary data consists of rainfall intensity from the Indonesian Agency for Meteorological, Climatological, and Geophysical Research at Karangploso local office, Malang District, and a geologic map from the Ministry of Energy and Mineral Resources of the Republic of Indonesia. Finally, the third phase is data integration and representation to establish the relationship between all supporting data and the landslide occurrence. The final product is a digital map of the potential landslide areas after the compilation of the parameter control data.

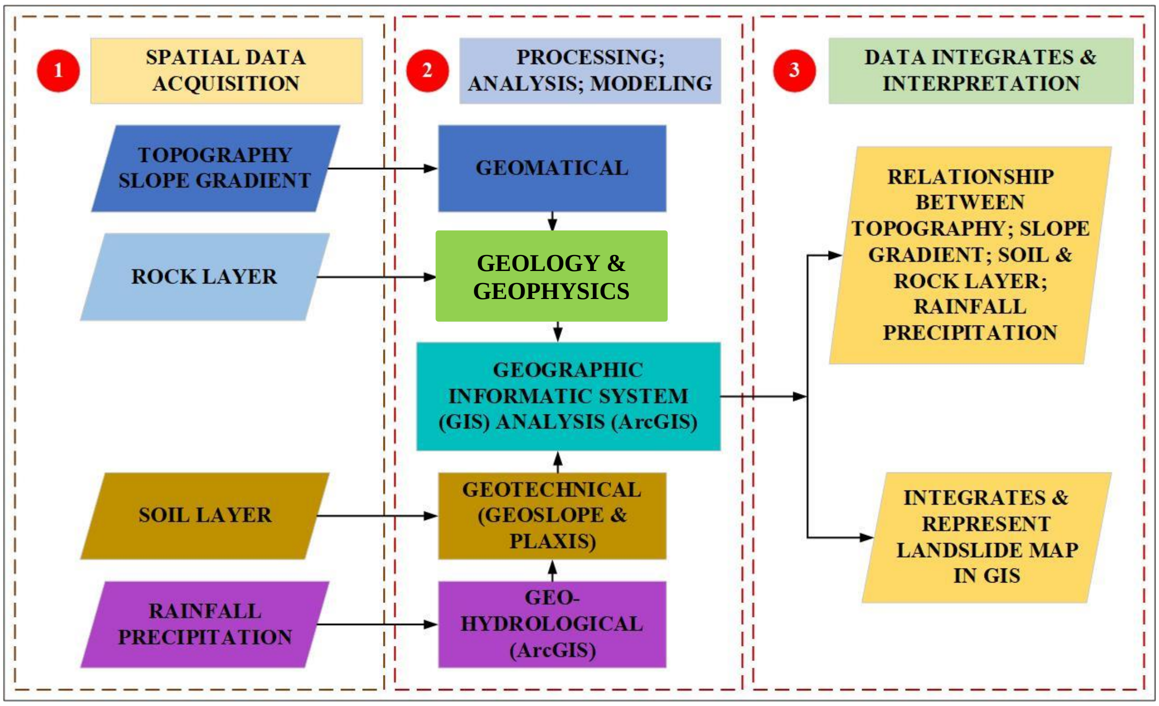


Figure 3. The simplified methodology structure to produce the digital map for landslide

3. Research Results

3.1. Geomatical Data

Geomatical measurements using drone devices were conducted to validate them with a topography map produced by the local KWB government, as shown in Figure 4. Figure 4 shows the imagery of the Payung zone, where the land covers in real time from aerial photography. Quantitative data results show that the gradient slope varies between 8 to 45% in the region (Figure 5). Curvature describes the physical characteristics of a drainage basin, including erosion and runoff processes. The land cover consists of wetland, forest, bush, grassland, farmland, barren, and settlement villages. Land cover obtained from the imagery database shows that the vegetation scarcity was related to the landslide in the study area.

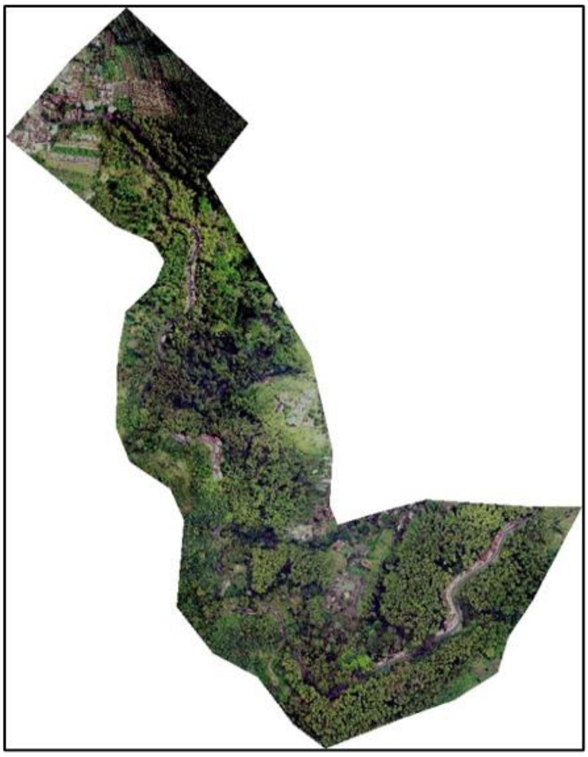


Figure 4. Orthotropic image in the real time of study area as a parameter of the geometrical data (Songgokerto Village, Batu city)

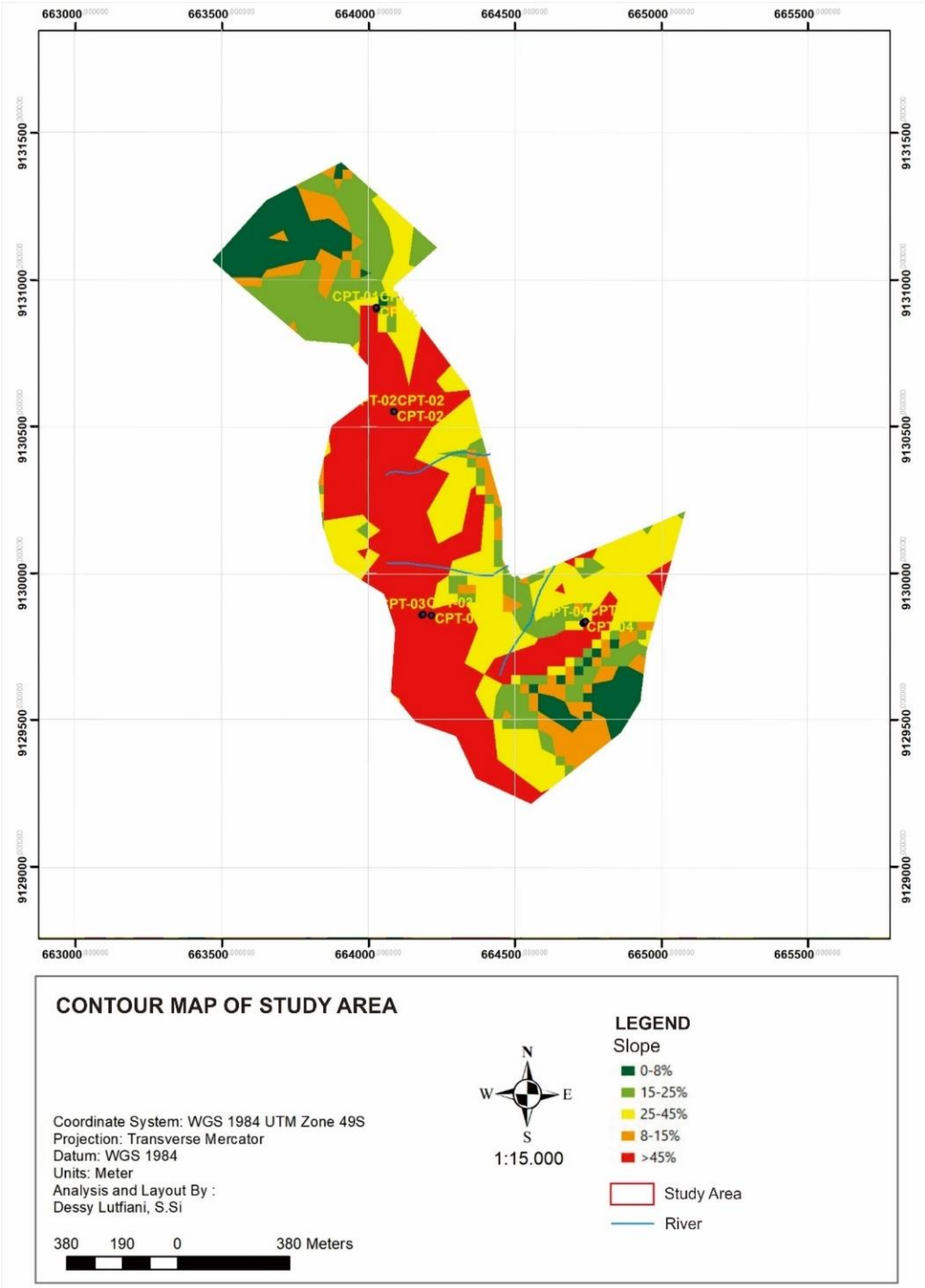


Figure 5. Variation of slope gradient in the study area

For example, one typical case, as shown in Figure 5, is shaded red as the hotspot area. This approach considers the landslide topography exposure as a result of the hazard frequency during the rainy season's incidence as spatial-temporal triggers, where the landslide potential uses average monthly rainfall to obtain a first representation of the exposure layer. In this area exist the cone penetration test No. 3 (S-3) and the geoelectric lining points (Lines 3 to 6). The area zone has a maximum slope gradient (> 45%), indicating an area with high susceptibility to landslides, and the condition of the road is in the middle of a cliff with a steep slope. The results of aerial images or photography from the air obtained were validated by field observation and geo-surveying measurements. Figure 6 shows the cross-section of the ground surface in lateral and longitudinal directions at the study area of the shaded area. The data results demonstrate the relevance of a multi-scale approach between aerial images and direct measurement in the field; at the specific level, the geomatical variables were able to detect landslide hotspot areas. The geomatical assessment for the hotspot area suggested a sliding line for further analysis from geophysical, geotechnical, and geo-hydrological points of view.

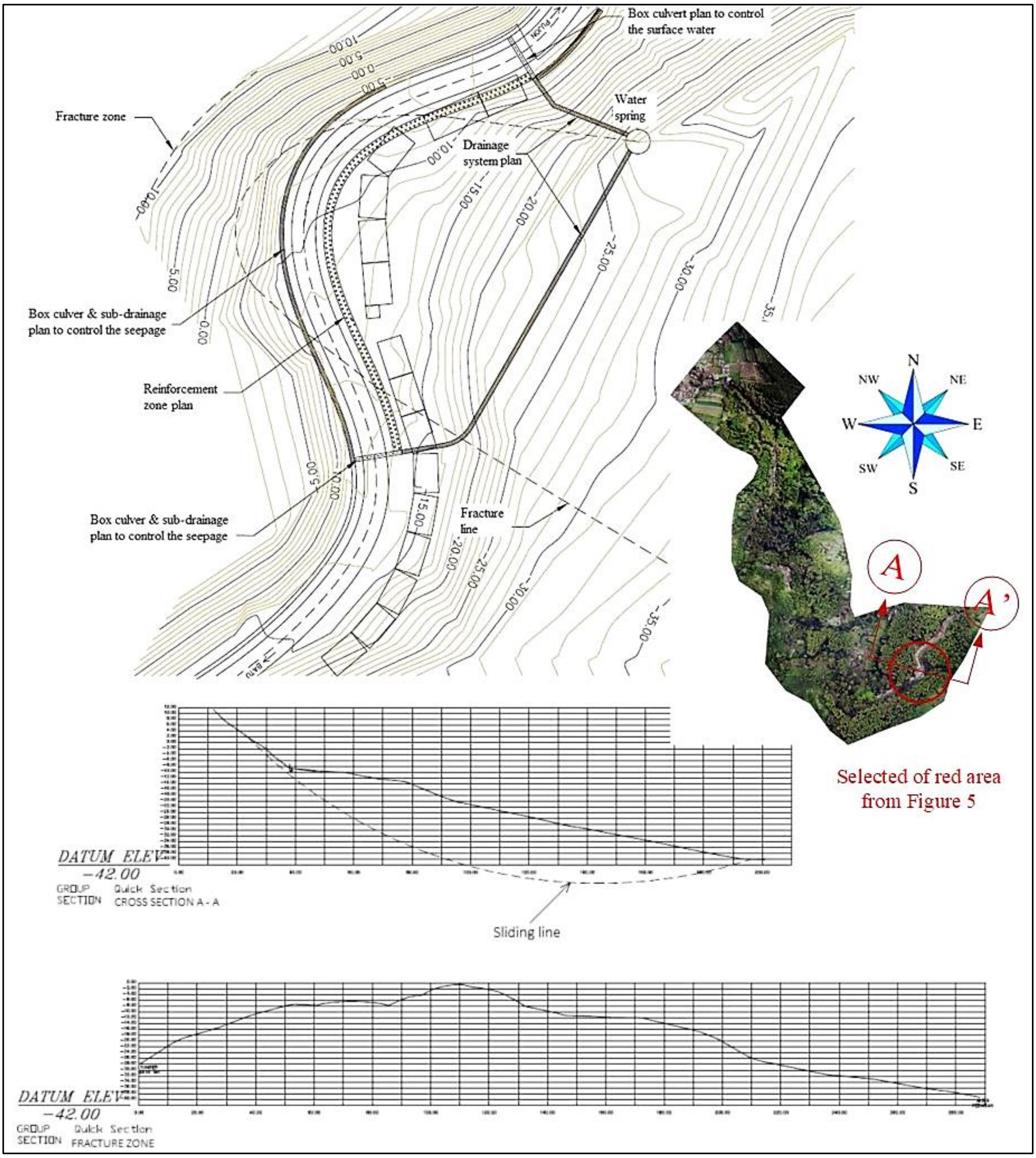


Figure 6. Typical transversal cross-section of the ground surface (at CPT for S-3 & Line 3 – Line 6)

Qualitative analysis results from geomatical parameter data supported the global climate change as a dramatic domino effect, however, the topography factors are not sufficient to explain the probability of hazardous phenomena in particular landslide susceptibility areas. Therefore, geomatical parameter supporting data must be used in a specific analysis on each independent variable quantitatively in geophysical, geotechnical, or geo-hydrological analyses.

3.2. Geophysical Data

Qualitative analysis used a geological map of Kediri Quadrangle (1992), as the secondary data, the geological conditions of KWB as seen in Figure 7. It can be found that Trunojoyo street in the Payung area and Songgokerto Village include the two formations. The first formation of volcanic rock of Old Anjasmara Volcanics (Q_{pat}) and classified as an aging prediction in the first Pleistocene era. The structure of the rock included volcanic breccia, lava, tuff, and easy to crack. Then, Panderman formation was formed by Upper Quarter Volcanic Formation ($Q_v(p)$) and aging classified in the Holocene era where rock structure consisted of volcanic breccia, breccia tuff, and tuff.

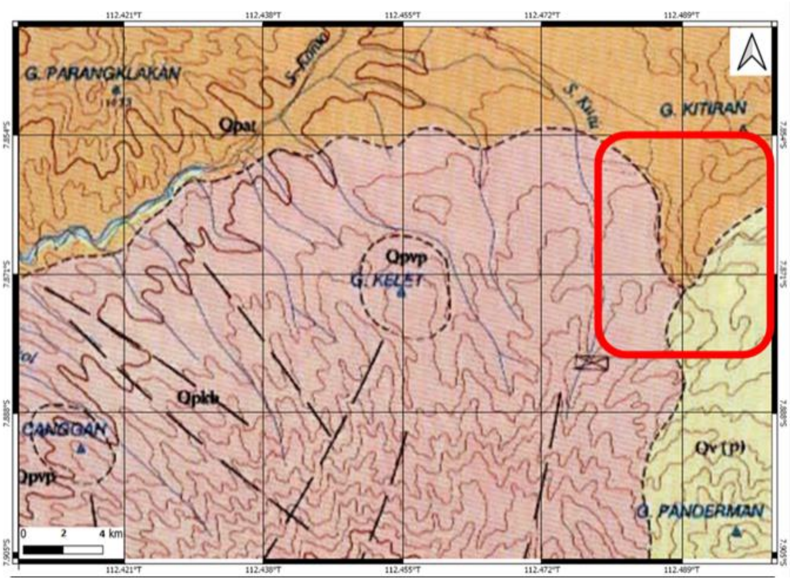
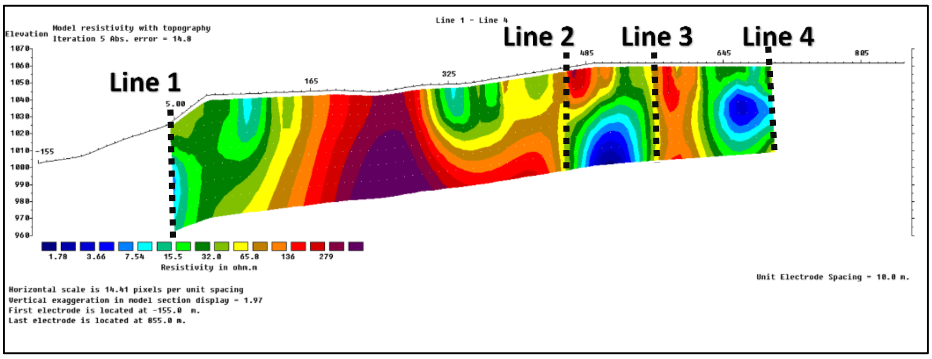
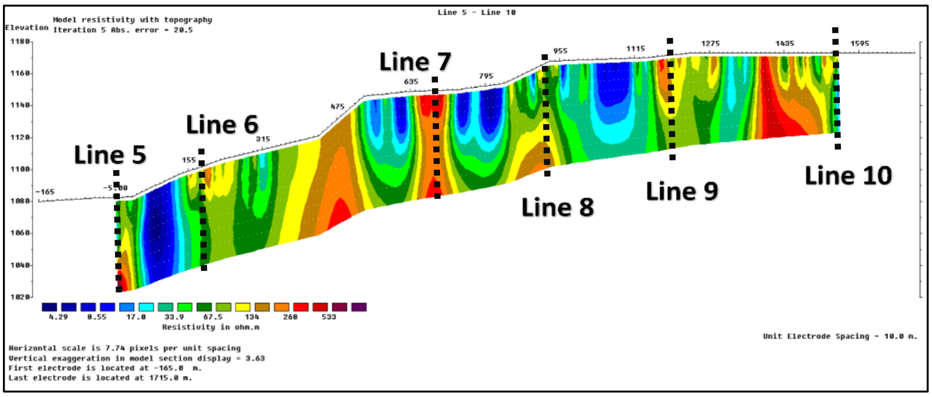


Figure 7. Geology map for Kediri Quadrangle [10]

The measurement results of the geoelectrical method are correlated with the geological map of the Kediri sheet, meaning that the theoretically measured rocks will be the same as the rocks on the geological map. Based on Figure 8-a, the measured resistivity value is between 1.78 Ωm – 279 Ωm for Upper Quaternary Volcanic Formation, while based on Figure 8-b, the measured resistivity value is between 4.29 Ωm – 533 Ωm for Old Anjasmara Volcanic Formation. Although in the same area, the two results have different resistivity values due to differences in rock formations. The measured rock types include tuff breccia and clay in the surface layer of the soil with the lowest resistivity values (blue color) of 1.78 Ωm – 7.58 Ωm (Qv(p)) and 4.29 Ωm – 17.0 Ωm (Qpat). The next layer is breccia and tuff with moderate resistivity values (green-yellow colors) of 15.5 Ωm – 65.8 Ωm (Qv(p)) and 33.9 Ωm – 134 Ωm (Qpat). Meanwhile, the last rock layer is interpreted as lava rock with the highest resistivity values (red-brown colors) about 136 Ωm – 279 Ωm (Qv(p)) and 268 Ωm – 533 Ωm (Qpat).



(a)



(b)

Figure 8. Longitudinal cross-sections (A-A') in 2D from Line 1 to Line 10 of geo-electric method (a). Upper Quaternary Volcanic (b). Old Anjasmara Volcanics

In the Old Anjasmara Volcanic Formation, lava rock was found with a shallowest depth of 20 meters, while in the Upper Quaternary Volcanic Formation, it was found at depths above 50 meters. Theoretically, encountering the layers of lava rock with the previous rock can become a slip plane zone, there is a face-off of two rock layers that are quite contrasting [11]. The layer contrast will then become the slip plane zone, this is due to the difference in density of the two rock layers. If the layer that has a lower density is saturated with water, it will have the potential to experience movement or landslides, so this zone becomes quite dangerous. Based on figure 8, the blue color shows the lowest resistivity value, in this case, it is interpreted as clay rock, where clay rock has a fairly low density and is easily filled with water so that the meeting of the blue and red layers (high density) becomes a weak point or slip zone like as Line 4 and Line 5.

Based on data from the Batu City BPBD (Regional Disaster Management Agency), this area is the location of the most landslide events and occurs frequently, especially for CPT-3 & Line 3 – Line 6. So that the confluence of the two rock formations needs to be further studied to analyze its relationship with landslide events. Thus, the encounter between volcanic rock and previous rock layers could be a slip plan for the landslide zone. This zone is not only a trigger for sliding lines, but also it can be active during the rainy season. The different behavior due to the age of the rock in both these layers extremely also contributes to material movement in the landslide event. Weathering process can occur when the clay rock layers absorbed more water during high rainfall. The change in weight volume will be a trigger for the material movement towards the slope.

3.3. Geotechnical Data

Data samples were taken from the study area by using CPT (Delft biconus patent) with a capacity of 2500 kg or 2.5 tons. This test was used to predict the soil layer until the hard layer. CPT data includes cone resistance (q_c), friction sleeve (f_s), and friction ratio (F_R) as shown in Figure 9.

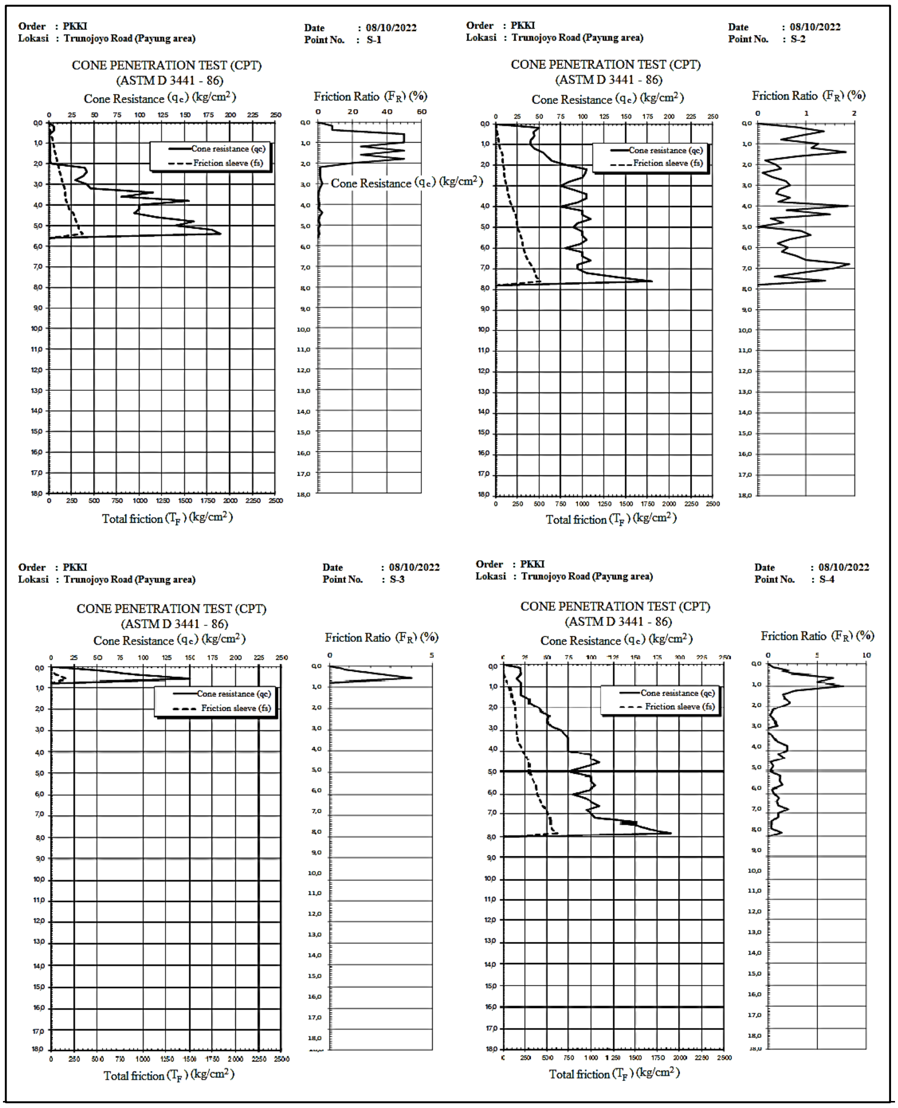


Figure 9. Typical CPT data from S-1 to S-4

Pre-drilling had to be conducted at every location of the CPT test in the study area since the location was near or beside the access road from Malang District (Pujon area) to KWB. At the 4th point data (S-4) conducted at the field shows that between 0.20 to 1.00 m from the ground surface, cone resistance (q_c) varies between 20 kg/cm^2 to 35 kg/cm^2. However, the q_c value decreased and reached 7 kg/cm^2 at the depth of 1.80 to 6.40 m. Then, the cone resistance increased from 85 kg/cm^2 to 210 kg/cm^2 at the depth of 7.80 to 8.0 m. The friction ratio (F_R) near the surface is larger than the layer until 1.20 m and reached 5%. It could be predicted that these layers had been compacted during road construction or repaired construction after a landslide occurred in Figure 9. Average values of F_R had a constant value below 2.5 – 3.0 %. From these data, it can be found the slip line or plane during landslide existed between 7.0 and 8.0 m depth at the 4 points of CPT at the study area (S-1 to S-4).

In geotechnical analysis quantitatively, soil and rock parameters must be determined based on data from field or laboratory tests. Since the cone penetration test could not work to penetrate the soil layers (Figure 9 for S-3), the other field test method has to be performed to predict the important parameter for slope stability analysis. Two bore logs and a standard penetration test (SPT) were performed at this location. The result of two bore logs is shown in Figure 10.

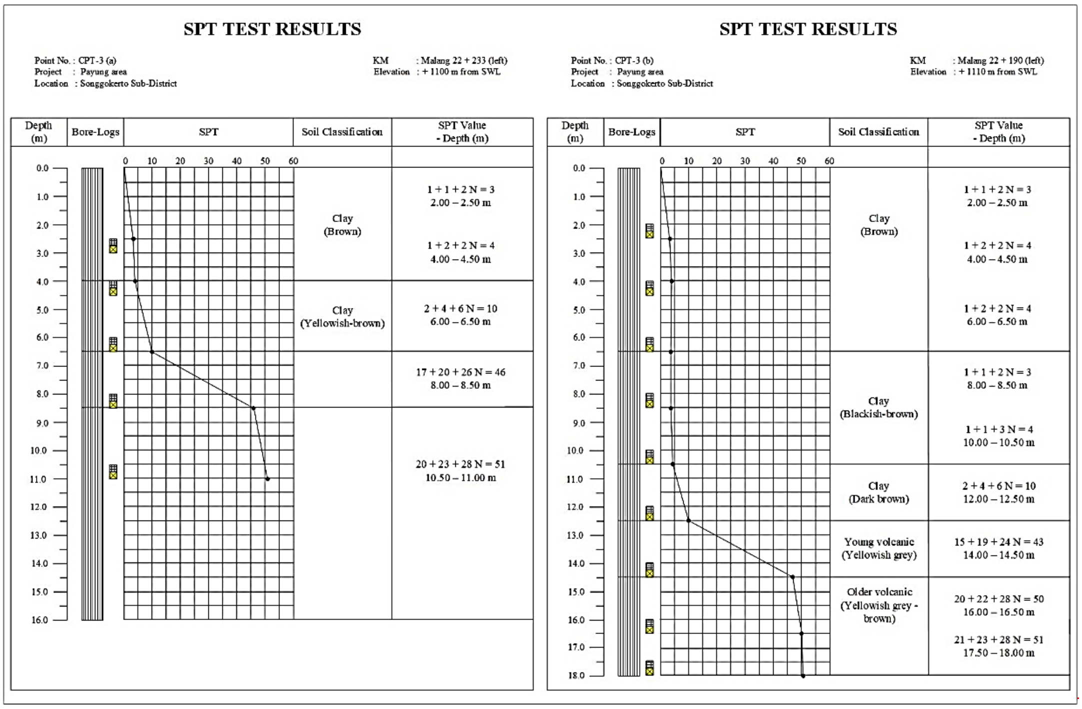


Figure 10. Typical SPT data recorded at the location of CPT-3

Slope stability analysis was carried out the finite element method. Analysis of the program uses two types of conditions with Mohr–Coulomb modeling, namely: analysis of total stress with the self-weight of the slope and traffic with or without earthquake loads, and analysis of effective stress where the normal groundwater level and self-weight of the slope. The typical results show in Figures 11 and 12 using the geotechnical software program.

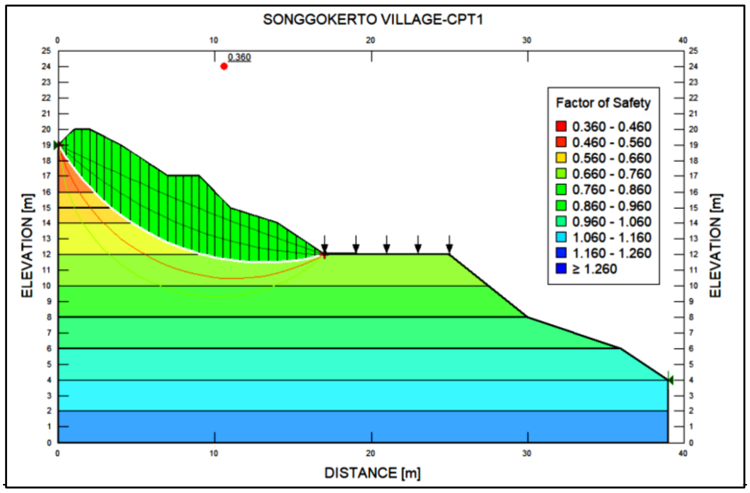


Figure 11. Typical assessment analysis results and traffic loadings when heavy rain over 2 hours without an earthquake

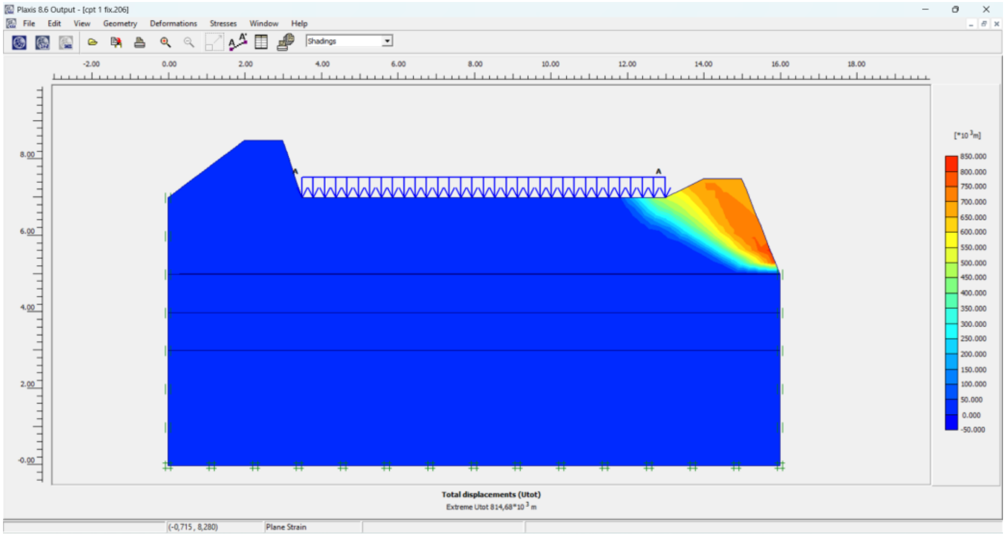


Figure 12. Typical analysis results with public traffic and without earthquake load

3.4. Geo-Hydraulic Data

From BMKG Climatology Office at Karangploso and BPBD at Among Tani Building Block Office, rainfall area intensity could be predicted and plotted by using a combination of ArcGIS and ArcMap analysis (Figure 13). Figure 13 shows that Songgokerto Village was classified from low to high rainfall intensity. Sumberbrantas and Tulungrejo Village had rainfall intensity of 875 to 3000 mm each year and rainy days with 110 to 134 days during time observation of 20 years.

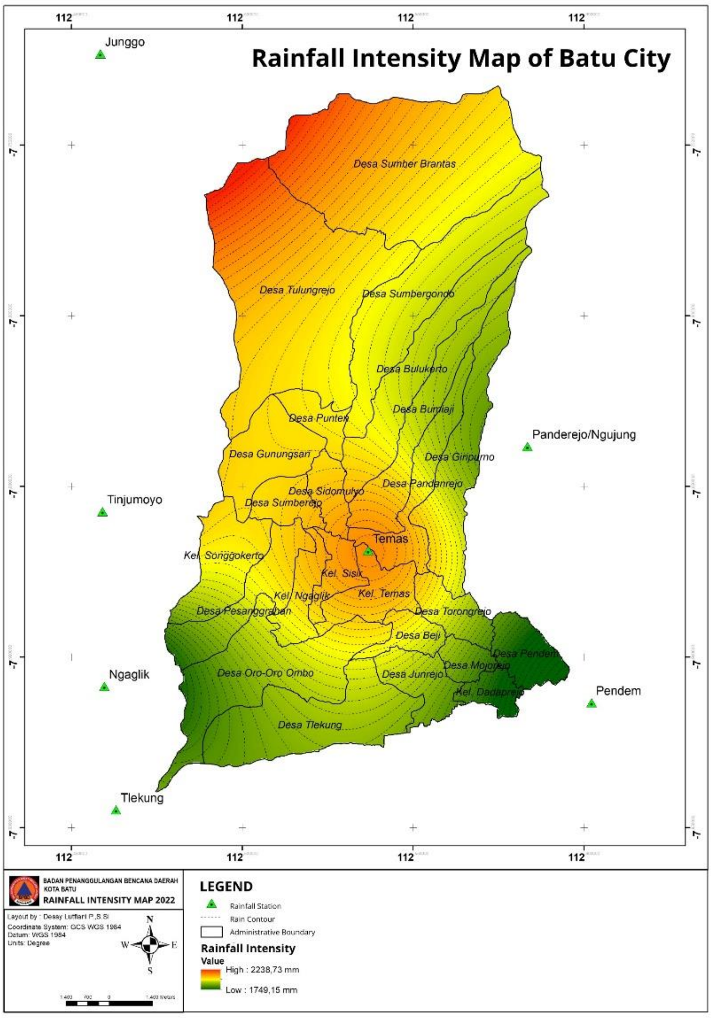


Figure 13. Rainfall intensity in Batu City

Runoff from rainfall was correlated with land slope. Unfortunately, the water from rainfall could flow into susceptible landslide areas and had the potential to slide and create hazards on access roads that existed in the study area. From the total area of KWB, Songgokerto had a 7.7% land slope area. The level of the land slope in this area was more than 40% where the access road existed from the Pujon area (Malang district) to KWB. The landslide could have occurred if the duration of rainfall was between 3 to 6 hours with a paused variation of 30 to 60 minutes in one day of hard rain of 875 to 3000 mm each year and a rainy day of 110 to 134 days during a 20-year observation period. The basic data compiled was also utilized to create a flow model at the ground surface on a digital map as one of the triggers of landslide occurrence due to seepage potential during rainy seasons (Figure 14).

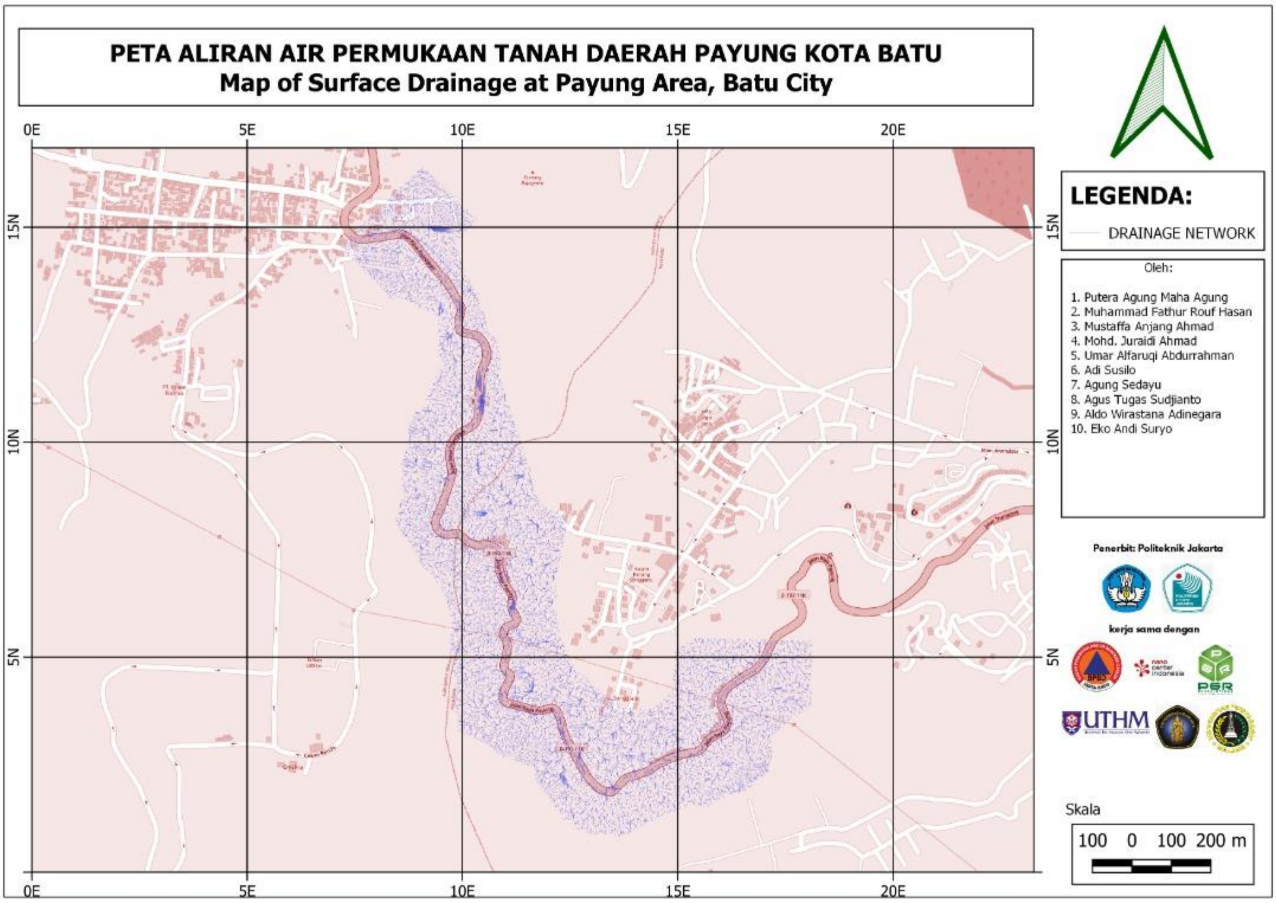
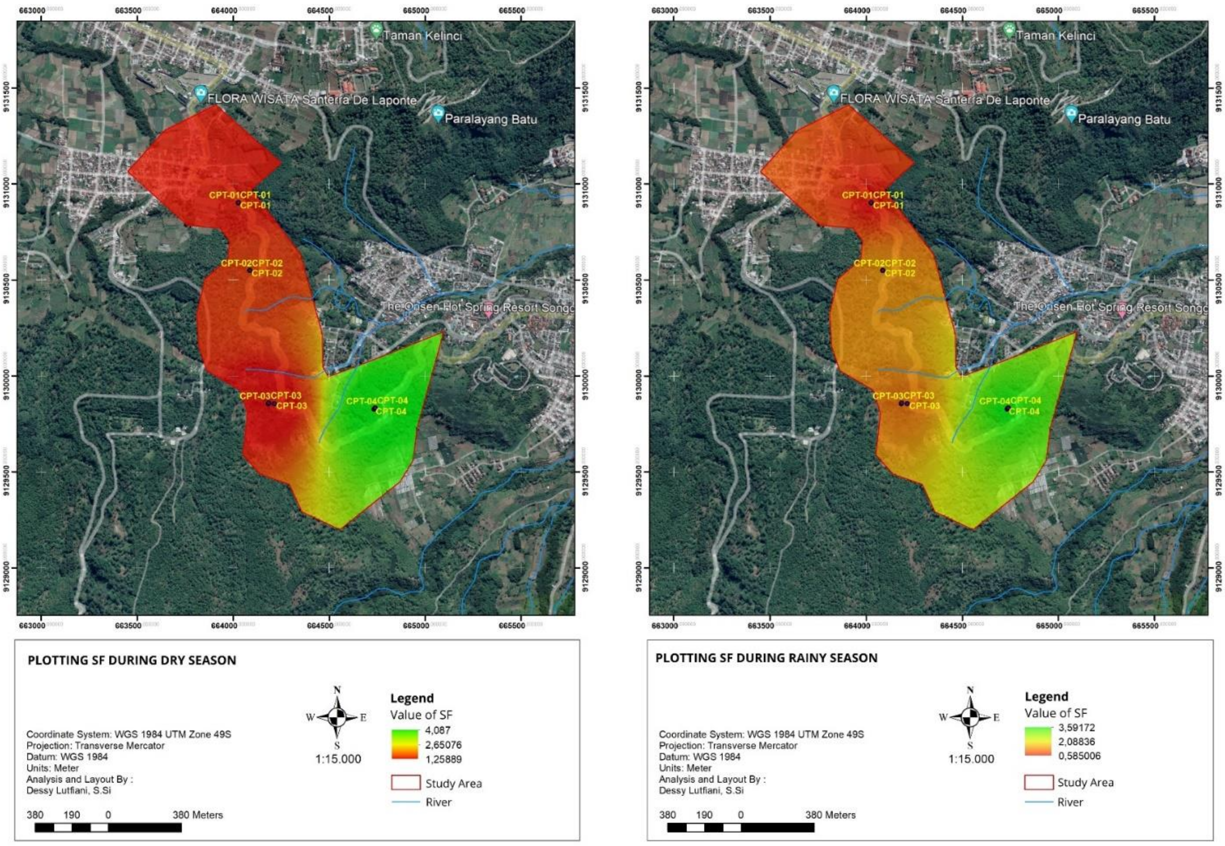


Figure 14. Assessment of surface drainage map at Payung area, Batu City

3.5. Assessment of Landslide Map

The lowest SF value is located at CPT-4. This soil slope is located about 2 km from Batu Sub-district towards the Pujon Village region. The road has been cut within the debris soil overburden; on average, the height of the cut slope ranges from 14.5 to 25.0 m. The cut slope is inclined at 66°. The thickness of the overburden is high ranging from 13 to 23 m. The slope consists of debris material, and angular fragments of volcanic rock, the fragment material like sandstone and/or clayshale. The embedded material was found along with a silty-sand matrix. The upper slope supports the thick vegetation of trees and bushes. Rotational debris failure was observed on this slope. The loose debris may fall during the rainy season. The factor of safety value was determined to equal 1.036 and 1.0 for completely dry and 30% slope saturation conditions, respectively, showing that the slope is just stable for these conditions, whereas the slope becomes unstable at the stage of 50% moisture content, for which SF is less than 0.925. Figure 15 shows the landslide potential during the dry and rainy seasons.

Both figures of landslide potential for CPT-1 and CPT-2 areas were more stable than the others (CPT-3 and 4 areas), with an SF less than 1.50 at completely dry conditions, while the remaining soil slope sections were stable at dry slope conditions. Two slope sections, namely, CPT-3 and CPT-4 areas, had SF less than 1.0 and hence unstable, while the remaining were stable with SF greater than 1.0 at 25% moisture conditions. In this analysis, quantitative, parameter data of geotechnical can be used to assess a digital map for slope sliding areas directly. However, this assessment must be validated by qualitative analysis to improve the map.



(a) (b)

Figure 15. Susceptible landslide area of KWB during (a) dry season and (b) rainy season

4. Discussion

From geosurveying measurements, the Songgokerto village area had a land slope and had the potential to landslide since the water from rainfall during hard rain would pass through this area. The soil grain and rock layers would be separated and swell rapidly, and finally, the ground would move in a slope direction. CPT and geo-electric tests also identified that Songgokerto village had a large potential to suscept due to hard rain over this area. High pore water pressure which passed these layers would cause a decrease in total shear strength, and finally, effective shear strength closing to zero. This situation would be occurred rapidly after the hard rain with a pausing time of 30 to 60 minutes during a rainfall of 3 to 6 hours. Some studies before this paper also show some supporting reasons that the Songgokerto area was always a landslide hazard, especially for the access road between the Pujon area (Malang District) to KWB. Alteration of land use around this study area would increase the landslide potential. Besides that, the traffic loading that always increases every year, the change of vegetation around the hilly by reforestation, human behavior in cutting down the trees to make an agro-tourism industry area and/or infrastructure, the poor drainage system of the access road, would be getting the worse situation. This area must be intensively studied to find out the suitable mitigation handling without destroying the existing good environment and good view from area study, monitoring, and evaluation are required to increase.

Various aspects in the analysis of the mechanism of landslide events in the Payung area are topography, geological and geotechnical conditions, land use, rainfall, groundwater and surface drainage, and the influence of human activities. The qualitative analysis is harder to apply than the quantitative analysis for the Payung zone because of the complex problems in the existing area. Previous study, the susceptible landslide area without consideration quantitatively or based on valid data in real time [3, 12–15]. This map can be assumed when it was drafted qualitatively only or based on some occurrence of landslides during past observation and probabilistic analysis. For example, the red area is not a more as susceptible area because the land use has been changed with reforestation and earth structure for the reinforcement of the slope area.

The present study showed the importance of integrating various factors that are responsible for landslide occurrence in the study area. However, the quality of the landslide inventory and the causative factor maps should be improved with good quality in time and space. Landslides in the study area have affected the local people who are living near the mountainous area, valleys, and gorges [16–20]. Besides preparing the landslide susceptibility maps of the area [21–26], suggesting the necessary preventive measures in the high and very high susceptibility classes is very essential to reduce the impact of future landslide hazards in the area [27]. Hence, this study recommends planting trees and vegetation, providing proper drainage, applying gabion and check dams, relocating people, and creating public awareness. To implement these remedial measures, further study on the geotechnical properties of soils and rocks should be conducted in this area when creating the digital map using geospatial analysis [28].

Geo-surveying or geomatical analysis results found that the Payung zone consists of a slope between 25–40% and a slope larger than 40%. From a geophysical point of view, it was identified that the upper quaternary volcanic rocks consist of breccias, lava, tuff, agglomerate tuff breccias, and lava. The formation of volcanic rock in the landslide zone is a susceptible area due to the weathering process and forms a layer of soft soil that is easy to move after the change of land use. In addition, the existence of a location near the contact of rock formations makes the rock masses above it easier to experience movement because there is a weak area in the form of rock layer contact, which can also be made possible as a slip plane. All cross sections from the geotechnical analysis show the landslide potential based on the safety factor (SF), where in the dry season the minimal SF value exists at SF = 1.26 and in the rainy season the minimal SF value reaches 0.58. Geo-hydraulic studies found that the potential precipitation or rainfall, especially during the longest duration time, contributed to the slope sliding.

5. Conclusion

The digital mapping presented here has combined the 4 (four) subjects, such as geomatical, geophysical, geotechnical, and geo-hydraulic aspects, as the parameter control data, both qualitatively and quantitatively. Geomatics with geo-surveying is used to find out all the cross-sections of the ground surface in lateral and longitudinal directions and to obtain some basin areas that have the potential to collect water on the surface and create the highest pore water pressure. Geophysical analyses can also determine the age and type of soil and rock layers, their behavior (weathered or not weathered) during loading or unloading by the water flow, the slip plane in soil and rock layers, the fluctuation of groundwater table elevation, and the groundwater flow pattern during dry and rainy seasons. Geotechnical engineering can observe all cross-sections to determine the areas that have landslide potential based on a safety factor (SF) computer-based system for simulation analyses. Geo-hydrology can analyze flow patterns above and below the ground surface (laminar or turbulence), and geo-hydrology can also find the catchment area model that will be suitable for landslide areas, especially during the longest duration of precipitation or rainfall.

The integrated analysis using four subjects can avoid mistakes or errors both qualitatively and quantitatively. The product of a digital map is very dependent on the quality of parameter control data. For example, rainfall intensity can be the most important factor in landslide occurrence, according to a study based on geo-hydraulic data. There are three types of landslide occurrences in the Payung area of Batu City, such as major landslide occurrence, minor landslide occurrence, and no landslide occurrence. However, the rainfall parameter is also very closely related to slope gradient, characteristics of soil and rock layers, pore water pressure, and land use to predict the potential occurrence of landslides. The results of a digital map of landslide potential can be easily read by the public. Classification by safety factor values (SF) can be verified using historical landslide occurrences. The digital potential mapping would be useful as an early warning of landslide occurrences and as a prediction tool for future potential landslides in development and land-use planning, and landslide risk management.

Digital landslide mapping can be updated time by time according to the change in human activities in plantations, agriculture and/or tourism areas, and reforestation programs. Measurement data found that the average slope angle is around 40–50º. Studies from geophysical data identified that the hilly terrain in the object study area has been dominated by the weathered rock layer. Geotechnical data obtained shows the soil layers at the slope location will be stable with the water content under 35% during dry season and may become unstable with the water content reaching over 50% due to the increase in saturation during the rainy season. An unstable slope can occur by increasing the pore water pressure during the seepage process. The landslide that occurred was more caused by seepage behavior from surface water flow towards the sloping plane, and then, the safety factor during the rainy season reached the critical values at SF = 0.58. During the dry season, the unsaturated process due to the temperature change generates a safety factor (SF) of more than 1.2. The compilation data produced the mapping of susceptible landslides and surface flow distribution.

6. Declarations

6.1. Author Contributions

Conceptualization, P.A.M.A. and M.F.R.H.; methodology, P.A.M.A. and M.F.R.H.; software, U.A.A. and M.J.A.; validation, A.T.S., M.A.A., A.S., and E.A.S.; formal analysis, P.A.M.A., M.F.R.H., and M.J.A.; investigation, P.A.M.A., M.F.R.H., and A.T.S.; resources, P.A.M.A.; data curation, M.A.A., E.A.S., and M.J.A.; writing—original draft preparation, P.A.M.A. and M.F.R.H.; writing—review and editing, A.T.S., M.A.A., A.S., and E.A.S.; visualization, U.A.A.; supervision, M.F.R.H.; project administration, M.F.R.H. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

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6.5. Conflicts of Interest

The authors declare no conflict of interest.

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