Hydro-meteorological hazard assessment at a local scale by using a physically based model in Central Java Province, Indonesia

FARIED RAHMANY
February, 2018

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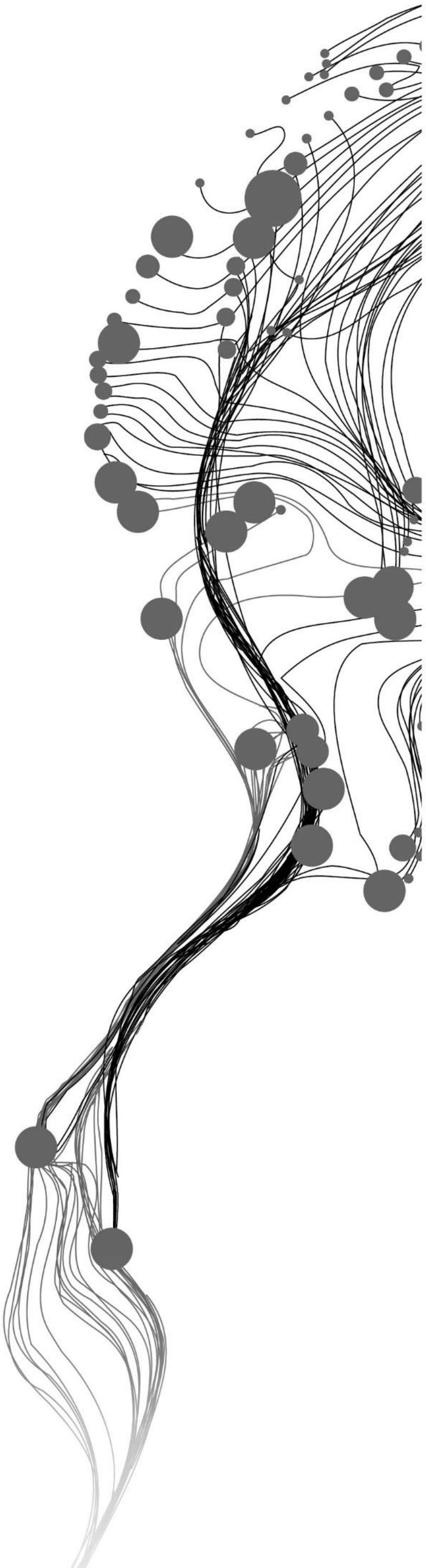

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Enschede, The Netherlands, February, 2018

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfillment of the requirements for the degree of Master of Science in Geo-Information Science and Earth Observation.
Specialization: Applied Earth Sciences with specialization in Natural Hazards, Risk, and Engineering

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ABSTRACT

In 2011 and 2014, the largest landslide events took place in Bompon and Karangkobar, Central Java Province, Indonesia. Both of the events occurred in December, which is known as the rainy season. Several Landslide Early Warning System (LEWS) have been installed in many areas which are prone to landslides in Indonesia. This LEWS usually consists of an extensometer to detect the soil movement, a rain gauge, a siren, and a solar panel. However, the LEWS only covers one or several slopes, besides, it is also expensive and prone to human interferences. Considering the drawbacks of the LEWS, another method was proposed in this study. The event-based physical model by using the new Open Lisem was used to investigate its capability to simulate the hydro-meteorological hazard in the area. The objective of this study is to use the physical model results, which are safety factor map, debris flow height map, and flood depth map, with different rainfall scenarios and combined with homogeneous units, in order to develop a local early warning system.

The main methodology for this study was to generate the homogeneous units and perform the physical modelling by using the new Open Lisem and combine both of the results to find out the hazard types for each unit. The homogeneous unit used in the study was settlement with different slope angles. The settlement unit is more important in term of giving warning, due to the fact the landslide occurrences in the areas mainly in or near the settlement. The physical model results for both study areas were validated by the landslide events in 2011 in Bompon and in 2014 in Karangkobar. The validation results for both study areas were totally different. The new Open Lisem could not predict the landslide in Bompon, due to the landslides in this area mainly at cut slope, whereas over-prediction results were obtained in Karangkobar.

The combination of settlement unit and physical modelling with three different rainfall scenarios reveals that the hazard level for each settlement unit is almost similar and tends no differences for each rainfall scenario, particularly to the result of the slope failure (SF < 1) and debris flow. Due to no significant differences for each scenario, therefore, the warning is applied equally to the settlement units which are affected by those hazards with the highest warning level if the rainfall in scenario 1 is exceeded.

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1. INTRODUCTION

1.1. Background

Indonesia is susceptible to geophysical and hydro-meteorological hazards, due to its geological conditions as Indonesia is located on the Pacific Ring of Fire (an area with a high degree of tectonic activity) and the tropical climate with high precipitation (Sutikno, 2007). Floods and landslides are known as the most frequent hazards. According to Indonesian disaster data and information (BNPB, 2017), there were 8,570 occurrences of landslides and floods during 2010 – June 2017 which caused 2,485 casualties, and roughly 1,795,576 people were evacuated.

The anthropogenic factor also plays a role in the occurrences of the hazards, because Indonesia has high population density, particularly in Java (BPS, 2017). The number of people is increasing year by year, subsequently rising the demand for housing and settlement. The settlement areas are mainly located in the lower part of the unstable slope. Besides, the land use change due to the agriculture expansion on an upper slope also plays a role in the increasing runoff and land degradation that leads to the occurrences of landslide and flood in the rural area (Marfai et al., 2008; Hadmoko et al., 2017).

Consequently, there should be mitigation efforts to minimize the impact of hydro-meteorological hazards to the human life or property. These efforts can be made either in the structural method (retaining wall, drainage tunnels, stone columns, etc.) or in the non-structural method, such as avoiding to build the houses in the area prone to hazards. However, due to the limited area and financial resources, this non-structural technique is not always feasible.

Landslide early warning system (LEWS) is another type of mitigation measure. There were several studies for predicting the rainfall-induced shallow landslide at a large area as an early warning system in Indonesia using the satellite rainfall data sets. Takara et al., (2009) developed a shallow landslide early warning system with the satellite rainfall product in West Java. Liao et al., (2010) made a prototype for predicting landslide triggered by rainfall in Central Java. On the other hand, the LEWS has also been implemented at a local scale which comprises the extensometer and the siren and installed at one or several slopes, such as in Banjarnegara (Fathani et al., 2008) and Karanganyar (Karnawati et al., 2011). At site-specific scale, EWS involves the installation of equipment, which however requires well-trained people to understand and operate it. Those EWS are usually limited only to one or several slopes coverage. Besides, the equipment itself is expensive and in many cases damaged by the interference of people or animals. Landslide EWS requires the involvement of local communities to participate actively to ensure the sustainability of disaster management program (Karnawati et al., 2009).

In this research, the focus is not on in situ monitoring techniques for the establishment of rainfall threshold for landslide initiation. Instead, it is for investigating the adequacy of an event based physical model. The objective is to use the result from this analysis to propose different actions to be taken, for the landslide risk management and the protection of the people. The combination of physical modelling with the rainfall scenarios gives different results on the occurrence of slope instability (debris slides and debris flows) and floods. Slope instability is assessed in terms of the factor of safety. The physical modelling analysis results from this work can be used by the local authorities to identify where and when the studied of hydro-meteorological hazard events are likely to occur and assist them to eventually provide the early warning for local people.

1.2. Research Problem

The 2011 landslide in Bompon and the 2014 landslide in Karangkobar were the most severe landslide events for both areas. These events made a considerable loss and caused many damages to houses and roads, and fatalities, especially in Karangkobar. Considering the frequency of a landslide occurrence in Indonesia, then the National Disaster Mitigation Agency (BNPB) together with the University of Gadjah Mada and Geological Agency of Indonesia have installed several Landslide Early Warning System (LEWS) in many locations in Indonesia

In Bompon there is one Landslide Early Warning System that has been installed in the settlement area in 2015 by the Local Disaster Mitigation Agency (BPBD) Magelang. It consists of the extensometer which equipped with the solar panel, a rain gauge and a siren. The rain gauge and a siren are installed close to the extensometer location. If the cumulative rainfall exceeds the threshold and there is a soil movement which is detected by the extensometer, the siren will be on automatically to warn the people. However, this LEWS only covers for one slope, and it is prone to human or animal interferences, such as the misuse of the equipment due to no sense of belonging by the community (i.e., used as a place to dry food or clothes) (Figure 1-1), and eventually disrupt the performance of the LEWS itself.

Figure 1-1 An example of human interference to LEWS

In addition, the use of rainfall threshold for defining the landslide initiation in the area only based on the approximation of the historical rainfall-triggered landslide in another area. During a short interview, the head of the village mentioned that the approximate rainfall threshold that leads to landslide is around 55 mm rainfall accumulated within 5-hours duration. He assumed that the villagers should be warned when this type of rain occurs, however he could not identify the location where the landslide might occur

Concerning those limitations, a new method for the warning is proposed. The event-based physical modelling used in the research will result in data for the spatial distribution of the expected slope failures (in terms of factor of safety), the expected debris flow extent and height, and the flood depth and extent. By using the suggested physically based model and applying different rainfall scenarios, it is possible to provide information about the type of the hydro-meteorological hazards which are expected in the different areas of the village and eventually will provide more specific recommendation for the different actions to be taken in case of crisis.

1.3. Objectives and Research Questions

General objective:
To use physically based model results for assessing the slope stability and the flood hazard in the study area, in order to develop a local Landslide Early Warning System, and to implement it into the landslide risk management.

The specific objectives and research questions that were addressed by this research include the following points:

- To generate a terrain subdivision based on homogeneous units considering hazard and exposure
    - What is the necessary DEM resolution for generating slope units in the study area?
    - What are the best parameters of slope units that suitable for hydro-meteorological hazards assessment?
    - Which subdivision method has a meaningful unit for hydro-meteorological hazards assessment for the study area?
- To perform a physically based modelling for hydro-meteorological hazards (slope stability, debris flow, and flood)
    - How can the physically based modelling be applied in the study areas for hydro-meteorological hazards assessment, given the types of hazard and data availability?
    - How to develop rainfall scenarios for the hydro-meteorological hazards modelling?
- To develop a local landslide early warning system based on the model results and the rainfall scenarios
    - What actions should be taken for each unit according to its characteristic?

1.4. Conceptual Framework

The goal of this study is to give different warning levels based on the hazard types of each unit. Therefore, three main processes are the main factors to achieve the objectives mentioned above; which are the rainfall scenarios which are incorporated to the physical modelling to define the degree of the hazard and the homogeneous unit for assessing the hazard in each unit. Finally, by using the hazard matrix lead to the suggestion of different warning levels for action to be taken (Figure 1-2).

1.5. Research Benefits

The benefits of the research are:

a. The outputs of the hydro-meteorological hazard simulation by using an event-based physical modelling can be used to assess the hazard occurrences in an area,
b. The integration of the different rainfall scenarios and physical modelling into the residential area provide the information about where and when the hazard is likely to occur, and subsequently can be used by the local authority to provide the warning for the local people.

1.6. Project Framework

Balai Litbang SABO (BLS) is a Research Centre under The Ministry of Public Work and Housing in Indonesia who has the responsibilities in systems control of erosion, sedimentation, lahars, and landslides. Recently, it has proposed an initiative to develop Landslide and Debris Flow Early Warning System. This proposal has been granted for an innovation project in 2017 and to be fully funded by the Indonesian Government as a multi-year research project. The EWS for landslide and lahar that will be developed is planned to use precipitation data from satellite products (e.g., IMERG, GPM) and forecast from European Centre Medium-Range Weather Forecast (ECMWF), which will be mirrored from the Badan Meteorologi Klimatologi dan Geofisika (BMKG). These data should be combined with landslide modelling, at two different scale: macro- and micro scale. At the macro scale, landslide susceptibility zones are combined with rainfall forecasts. In the micro-scale, landslide initiation models are used by integrating soil water modelling with slope stability calculation.

This study will be part the collaboration project between BLS and ITC by developing the direct hydro-meteorological hazards assessment incorporated with the physical model results that can be implemented for Landslide Early Warning System at a local scale.

1.7. Thesis Structure

Chapter 1: Introduction
Chapter 2: Literature Review
Chapter 3: Study Area
Chapter 4: Methodology
Chapter 5: Generation of the Homogeneous Unit
Chapter 6: Physical Modelling Using Open Lisem
Chapter 7: Application of the Early Warning System for Different Rainfall Scenarios
Chapter 8: Discussion and Conclusion

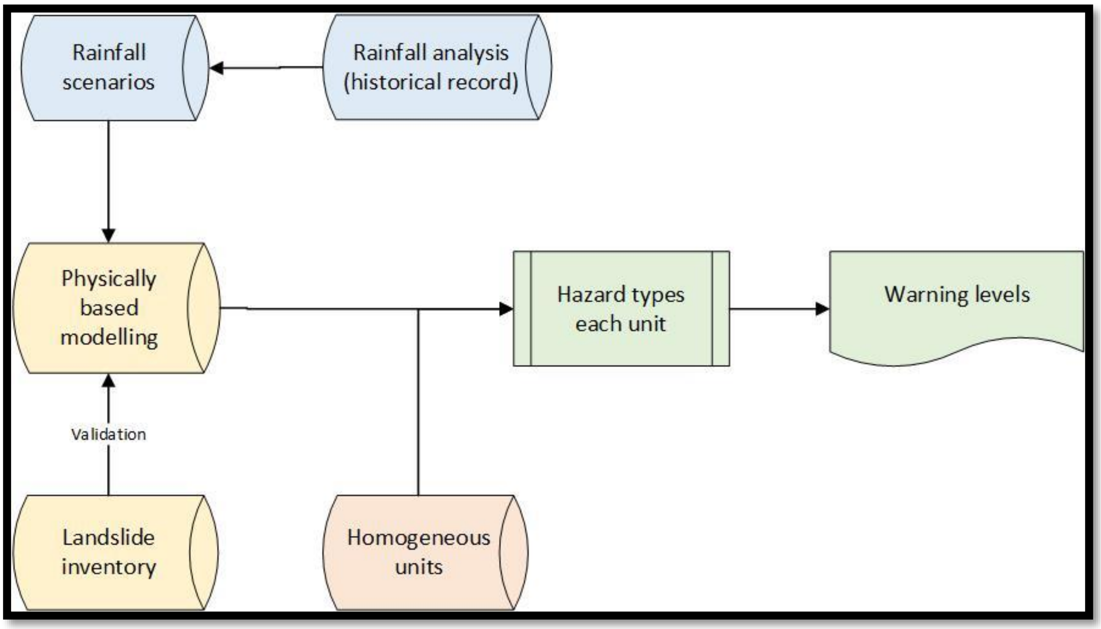


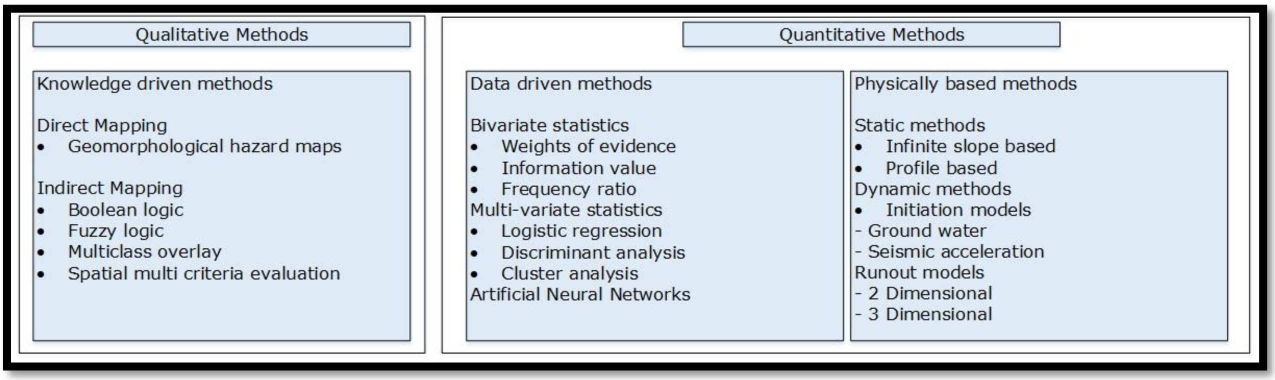
Figure 1-2 General conceptual framework of the research

2. LITERATURE REVIEW

Hydro-meteorological hazards refer to the processes of atmospheric, hydrological, or oceanographic nature that can cause physical, social, economic, and environmental disruption (UNISDR, 2009). Many factors are contributing to the occurrences of these hazardous phenomena, related to the environmental setting (topography, geomorphology, geology, soil properties) to the human activities (deforestation, road construction, agriculture expansion) as well as the occurrence of extreme rainfall intensity. Landslides, debris flows, and floods can be triggered by simultaneously or consecutively by extreme hydro-meteorological conditions.

In order to assess and investigate the landslide hazard for an area, it is essential to make an inventory of landslides. A landslide inventory refers to the information about the location, the type, date of occurrence, triggering factors, and other characteristics of a landslide in the area (Fell et al., 2008). There are several methods to prepare a landslide inventory, using conventional methods such as geomorphological field mapping and visual interpretation of aerial photographs, and innovative techniques, such as analysis of surface morphology and interpretation and analysis of satellite imagery (Guzzetti et al., 2012). Considering the humid tropical climate which influences the vegetation growth, then geomorphological field mapping seems the most applicable to be used in Indonesia (Samodra et al., 2015).

There are two standard categories in hazard assessment, qualitative (inventory based and knowledge-driven method) and quantitative (data-driven methods and physically based methods) (Soeters & van Westen, 1996; van Westen et al., 2006; van Westen et al., 2011; Corominas et al., 2013; Chen et al., 2016) (Figure 2-1). The knowledge driven method depends on the expert opinion, can be direct mapping (use of geomorphological map) and indirect mapping (use fuzzy logic, boolean logic, and spatial multi-criteria evaluation). Data-driven methods use the statistic to evaluate the probability of hazard occurrence. This method can be bivariate statistics, multivariate statistics, and artificial neural networks. Physically based methods use of spatial and temporal component as an input in the model, making the result is more realistic to the field and useful for hazard evaluation (Van Beek & Van Asch, 2004).



Qualitative Methods

Knowledge driven methods

Direct Mapping
- Geomorphological hazard maps

Indirect Mapping
- Boolean logic
- Fuzzy logic
- Multiclass overlay
- Spatial multi criteria evaluation

Quantitative Methods

Data driven methods

Bivariate statistics
- Weights of evidence
- Information value
- Frequency ratio

Multi-variate statistics
- Logistic regression
- Discriminant analysis
- Cluster analysis

Artificial Neural Networks

Physically based methods

Static methods
- Infinite slope based
- Profile based

Dynamic methods
- Initiation models

- Ground water
- Seismic acceleration

Runout models
- 2 Dimensional
- 3 Dimensional

Figure 2-1 Methods of hazard assessment (van Westen et al., 2011)

Physical-based modelling is used to describe the processes that lead to the occurrences of landslides. A typical output from physical modelling of landslide initiation is the factor of safety. The factor of safety (FOS) expresses the level of slope stability, and is defined by the equation below:

$$FoS = \frac{shear\ strength}{shear\ stress} = \frac{c+(\gamma * z * cos\beta)\tan\phi\prime}{\gamma * z * sin\beta} \text{ ....(Equation 1)}$$

where c = cohesion (kPa)

γ = soil specific weight (kN/m^3)

z = soil thickness (m)

ϕ' = internal friction angle (^{0})

β = slope angle (^{0})

If the safety factor is lower than 1, the slope is unstable, and if the safety factor is greater than 1, the slope stable.

There are several physical shallow landslide modellings that have been applied in different study area, such as STARWARS + PROBSTAB model that was developed by van Beek (2002) where it is a coupled model of slope hydrology and stability, TRIGRS model that was developed by Baum et al., (2008) which can generate the stability (based on the factor of safety) by calculating the water pressure and the rainfall infiltration, SLIDE that was developed by Liao et al., (2010) as their prototype Early Warning System for the landslides triggered by rainfall, and the new Open Lisem that was developed by van den Bout et al., (2017) where it integrates the flood and the slope failure calculation. The latter is a freely available process-based modelling software which is able to simulate both sediment and hydrological processes directly after a single rainfall in a catchment (Jetten, 2002). It is originally designed for simulating the runoff, flood, and soil erosion.

The new Open Lisem is able to calculate and simulate the slope failure, safety factor, debris flow, and flood. The outputs of this model are a slope failure map, a safety factor map, a debris flow velocity and height map, and a flood velocity and depth. The new Open Lisem is an event-based model which is primarily used to investigate the process of slope failure and debris flow and their interaction to the hydrology of a particular area at a short period. The event-based process, and the outputs of the model which offer more hydro-meteorological hazards, and the relationship of physical processes that lead to the hazard occurrences, make Open Lisem is competent for hazards assessment in a catchment.

The Open Lisem integrates the rainfall and infiltration in its simulation. The infiltration model used in Open Lisem is Green and Ampt (LISEM, 2016). The model assumes the wetting front moves downwards to the subsurface. Above the wetting front, the soil is saturated, and below the wetting front, the soil is completely dry (Figure 2-2). In the new Open Lisem, the calculation of slope stability is based on the wetting front (van den Bout et al., 2017). The wetting front can govern the slope instability by increasing the soil weight. If the infiltration of the wetting front is low, then the affected soil weight also low, and eventually only a small number failure occurs. In contrast, if the infiltration of the wetting front is high, the slope failure will be high too, as a consequence of the increases in soil weight. However, the infiltration rate is influenced by the soil types and the initial moisture condition (Ames et al. , 2001).

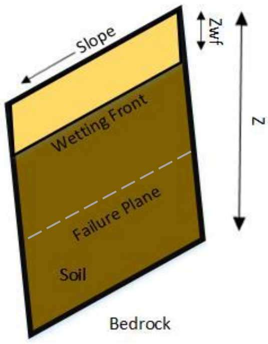


Figure 2-2 A simplified illustration of wetting front in the soil

Another important step in hazard assessment and zonation is the segmentation of the terrain into different units, with different characteristics that will define if they are in danger and by what type of hazard. Terrain units refer to the interrelations between materials, forms, and processes, and result in morphological boundaries that represent geomorphological and geological differences (Carrara et al., 1995; Guzzetti et al., 1999). They are used to create zonation in which the actual or potential hazards will occur in each unit. Carrara et al., (1995) have classified terrain unit into four groups, namely: geomorphological unit, grid-cell, unique-condition unit, and slope units (SU). Terrain units can be generated either manually or automatically. However, the manual method is time-consuming, and the result is prone to subjectivity.

Recently, a new method for delineating the slope units automatically by exploiting the Digital Elevation Model (DEM) with the specialized software r.slopeunits has been implemented by Alvioli et al., (2016). Slope units (SU) is a type of morphological terrain unit which is bounded by drainage (main streams) and divide lines (adjacent small drainage networks) (Guzzetti et al., 1999; Guzzetti et al., 2006). The application of slope units is more suitable for slow movement of landslide where this landslide type usually does not travel outside the slope.

The use of a Landslide Early Warning System (LEWS) becomes an important part of landslide risk reduction. According to the SafeLand project for EWS (2012), there are several important things for choosing the appropriate EWS to be applicable in a particular area, such as the landslide types, the scale of a landslide, and the lead time of the landslide occurrence. Regarding the lead time for giving the warning, it can be differentiated into two types: pre-trigger and post-trigger. Pre-trigger used the threshold to deliver the warning. If the threshold is exceeded (i.e., heavy rainfall), a warning should be given. Post-trigger used the evidence to issue the warning. Usually, post-trigger is used to give the warning for evacuation, but it always depends on the level of the hazard occurrence.

Physically based models offer the flexibility in simulating the occurrence of landslides for different rainfall scenarios, to find out the relationship of the landslide occurrences with the duration and the rainfall intensity (Schilirò et al., 2015; Wu et al., 2015; Gioia et al., 2016). This can improve the understanding of the landslides phenomena, and reduced the uncertainties related to their occurrences.

Additionally, physical modelling can provide information on the intensity and magnitude of the phenomena, that might lead to different levels of warning, such as the 2 or 3 warning levels (SafeLand, 2012). Two warning levels usually applied at a regional scale, and generally used for the occurrences of very short lead time of the landslides and employ the ordinary level (no particular action required) and alarm level (evacuation required). Three warning levels include an indication of the occurrences of some displacements and use the ordinary level (normal activity), pre-alarm level (small displacement occurred), and alarm level (more displacement occurred and needed evacuation). Warning levels, at graphics context, may be defined by using the colours, such as green, yellow, orange, and red, where they correspond to the degree of warning (Piciullo et al., 2017). Although most of the landslides EWS can issue an alert based on given rainfall thresholds, expert judgment remains the important factor to decide the type of the warning action (Thiebes & Glade, 2016).

3. STUDY AREA

3.1. Location and General Description

This research covers two study areas, including Bompon catchment and Karangkobar district in Central Java Province (Figure 3-1). The Bompon catchment is located in the upper part of Bogowonto catchment. It is administratively located in Salaman District, Magelang Regency, Central Java Province, Indonesia. This catchment consists of three villages, namely Margoyoso, Wonogiri, and Kuaderan, with a total area of 2.94 km^2. The altitude of this catchment ranges from 432 m – 558 m. The second study area is located in Banjarnegara Regency. The altitude of this area ranges from 481 m – 1324 m, and the total area is approximately 42 km^2. Both of the study areas are administratively located in Central Java Province

Initially, the fieldwork activities should be carried out for Karangkobar area, due to the largest landslide event in 2014. However, after considering the available data for physical modelling purposes, it was carried out in the Bompon catchment, Magelang. Still, the Karangkobar area was not excluded from the physical-based modelling and was also analyzed considering the data availability.

The Bompon catchment is used as a field laboratory for Geography Faculty of Gadjah Mada University. The main subject of this field laboratory is to study about the erosion in the catchment area. Therefore, since at the end of 2014, they installed four rainfall stations which measured the rainfall automatically with high temporal resolution (15 and 30-minute interval). They also installed a weir station at the southern part of the catchment for recording water level and eventually for measuring water discharge. These discharge data are important to calibrate the hydrological model.

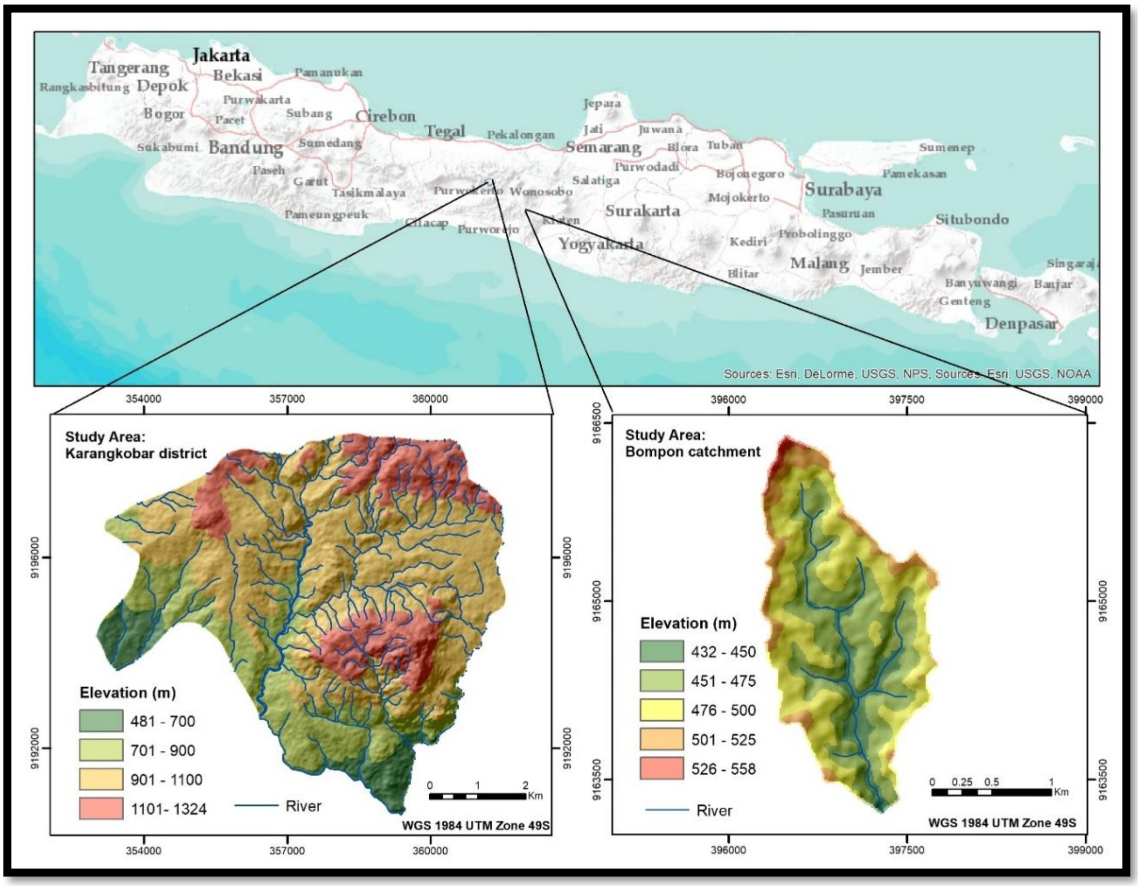


Figure 3-1 Location of study area in Central Java Province, Indonesia

The Bompon area is prone to landslides. The landslides occur almost every year, although most of the events occurred in a small area and did not cause too much destruction. However, there was a big landslide in 2011 which considered as the most severe due to the serious damages in houses and roads. The landslides occurred in several places simultaneously.

In 2015, there was a landslide mitigation simulation in Margoyoso village, in the southern part of the Bompon catchment, and it was conducted by the local disaster mitigation agency (BPBD) Magelang. This was done to give the local inhabitants the awareness of the landslide occurrences. In addition, the BPBD has installed one set of Landslide Early Warning System (LEWS) in the most populated settlement area, which located on the slope with several houses under the slope.

On the other hand, Karangkobar is one of the districts in Banjarnegara that is very prone to landslide. This area is even more prone to the landslide than Bompon. It suffered from more landslide occurrences, with larger effect. The biggest landslide events occurred in 2014 and caused many casualties and economic losses.

3.2. Land Use

There are 5 land use classes in Bompon area, which are dry cultivated land, mixed plantation, rice field, settlement, and shrub, where the largest area is mixed plantation (Figure 3-2 a). The dominant plantation consists of coconut, bamboo, banana, and other trees (i.e., sengon and mahoni). The latter is categorized as fast-growing plantation which is able to be harvested in 4-5 years. The products of coconut, bamboo, and trees have been the main revenue for the local inhabitants. The second largest area is a rainfed rice field which is planted during the rainy season. The settlement areas are mainly located on the lower and middle slope. The local inhabitants set up their area for housing by cutting the slope, and therefore, it makes this area prone to landslide.

On the other hand, Karangkobar is covered with 6 land use classes (Figure 3-2 b), with the dry cultivated land is the largest area and followed by the mixed plantation. In general, there are no significant differences in land use type for both areas since they are located in the same province, Central Java. However, the dominant land use type in one area reflect the livelihood in that area.

3.3. Geology and Geomorphology

The geology and geomorphology map for both study areas can be seen in annexes 1, 2, and 3. However, the geomorphology map only available for Bompon area.

According to Rahardjo et al., (1995), Bompon catchment is located on Kebobutak Formation which contains andesitic breccia, tuff, lapilli tuff, agglomerate and intercalations of andesitic lava flows. Geographically, the study area is bounded by Mount Sumbing at the north and Menoreh Mountain at the south. Consequently, this area is a mixing zone of new and old volcanic materials. Regionally, this area is not located in the fault zone or other geological structures. The high degree of weathered volcanic materials caused the difficulties to differentiate the soil and rock boundary in the field. These volcanic deposits are very thick and may cause problems, such as landslides and erosion.

In addition, the geomorphology map was obtained from UGM. The geomorphology unit was classified based on the morphology and the volcanic materials. There are 5 geomorphological units, namely Colluvial Plain, Lower Slope, Middle Slope, Upper Slope, and Crest.

Similarly, in Karangkobar, the predominant lithology is the volcanic materials. According to Condon et al., (1996), the area is located in several formations, such as Rambatan Formation which consists of shale, marl, and calcareous sandstone, Intrusives which consist of gabbro or gabbro porphyry, Clay Member of Ligung Formation which include tuffaceous claystone and sandstone, and conglomerate, and Jembangan Volcanics which comprised of lava flow, flow and pyroclastic breccia, lahar and alluvium. Moreover, this area is located in the complex geological structures, such as normal fault, thrust fault, and other lineament structures. These factors contribute to the occurrences of the landslide in Karangkobar area.

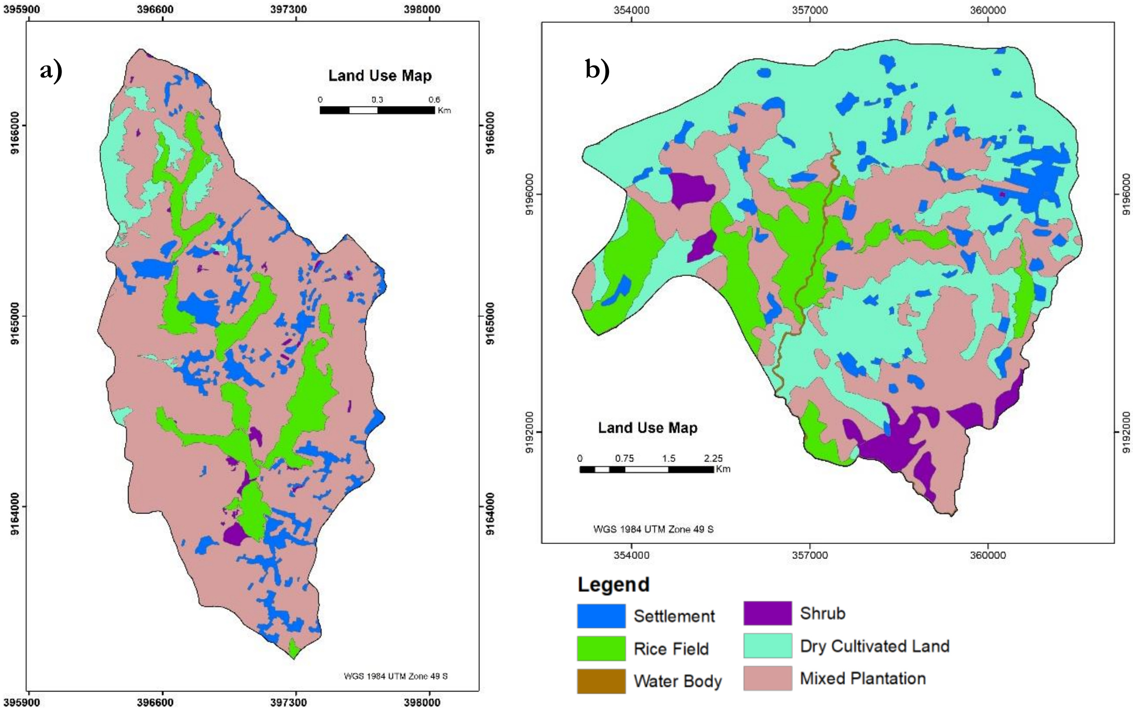


Figure 3-2 Land use map of Bompon (a) and Karangkobar (b)

3.4. Landslide Inventory

The landslide inventory for which the largest events took place for both study areas are used as validation data for the physical model results. It is necessary to do validation to see whether the model result fit enough with the inventory or not. Since the fieldwork was carried out in Bompon, the landslide inventory and landslide condition data are more complete than Karangkobar.

3.4.1. Landslide Inventory in Bompon

The landslide inventory of Bompon catchment was acquired from Ulfa (2017). It has basic information, such as location, time of occurrence, and dimension of the landslide. However, most of the landslide inventories were located outside the area. Therefore, during the fieldwork, this inventory was updated, especially in the area with no information of landslide and the type of landslides. In total, there are 25 landslide locations which could be found in the study area (Figure 3-5). The new landslide inventory was produced which includes the exposure elements (see annexes 5).

The main type of landslides in this area are shallow landslides which can be categorized as debris slides, cut slopes, and a deep-seated landslide (Figure 3-3). The deep-seated landslide is located in the southern part of the study area (Figure 3-3 b). This information was obtained during the fieldwork. To get such information mostly was done by asking the local people that experienced the landslide in the past. However, the majority of the people almost forgot about the exact time of landslide occurrences, and they remembered only it occurred during the rainy season. One interesting thing is, even their house was damaged by the landslide (a small part of the house, particularly kitchen) they still live there and rebuild the house at the same location and without doing some mitigation measures, for instance, make some terraces to reduce the slope steepness. The reason was mainly the limited land to rebuild the house (Figure 3-3 a). Therefore, to minimize the effect of rainfall that can trigger a landslide, they made a ditch along the slope for a water drainage to prevent the water flow directly to their area (Figure 3-3 c).

The largest landslide event occurred in December 2011 where several houses and roads were affected by the landslide materials, particularly in Margoyoso area. It was recorded that the event took place on 21 December 2011 and characterized by an excessive rainfall, which was 75 mm in a day. There were 8 landslide events recorded for this period, and no casualties reported during the landslide occurrences.

Figure 3-3 Landslides at Bompon and mitigation measure. One of the houses that were hit by the cut slope instability in 2011 (a), Deep-seated landslide (b), The drainage ditch along the slope (c)

3.4.2. Landslide Inventory in Karangkobar

The landslide inventory of Karangkobar area was obtained from Arrisaldi (2016). It covered the date of occurrences, location, type of material, and mechanism of movement. There was no other information about the landslide in the area, such as the landslide dimension and the damages caused by the landslide. In addition, the landslide inventories were improved with the information from local newspaper, short investigation report of Karangkobar landslide, and google earth imagery. The landslides runout data were obtained from manual digitation of google earth imagery, but there was no information about the landslides occurrence time. In total, there are 20 landslide points and 16 runout polygons in this area (Figure 3-6). The landslide inventory for this area can be found in annexes 6.

According to the landslide susceptibility zone map of Banjarnegara regency which is issued by the Center for Volcanology and Geological Hazard Mitigation, Karangkobar lies on low to high of landslide susceptibility zone (see annexes 10). The location where the biggest landslide occurred on 12 December 2014 was located on the high of landslide susceptibility zone, which means the area is very prone to landslide during high rainfall. This landslide event had devastating consequences. The landslide material destroyed the residential and rice field area (Figure 3-4). As a result, 88 people were reported to die, and more than 1000 people were evacuated. Also, the highway was cut off by the landslide and some debris blocks the highway.

Figure 3-4 The Karangkobar most significant landslide event in 2014 (photo was taken by Igan S. Sutawidjaya in Kristianto et al., 2015)

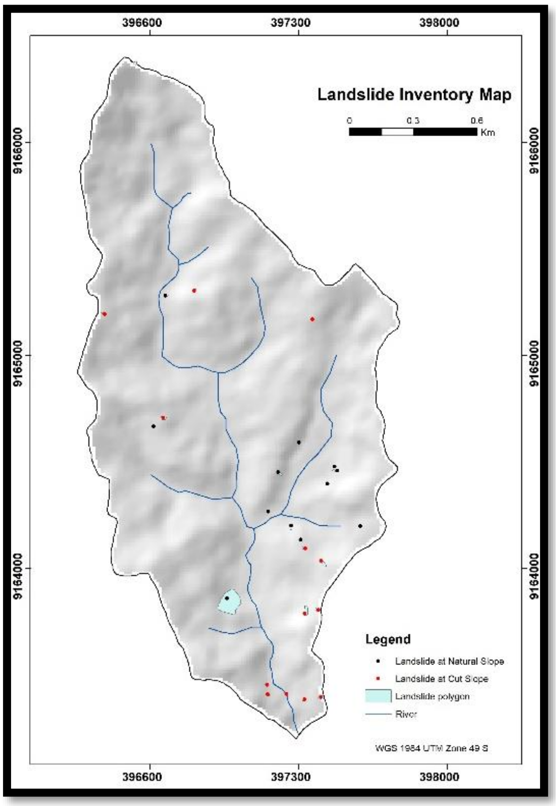


Figure 3-5 Landslide inventory locations in Bompon. The light blue colour indicates the largest landslide in the area.

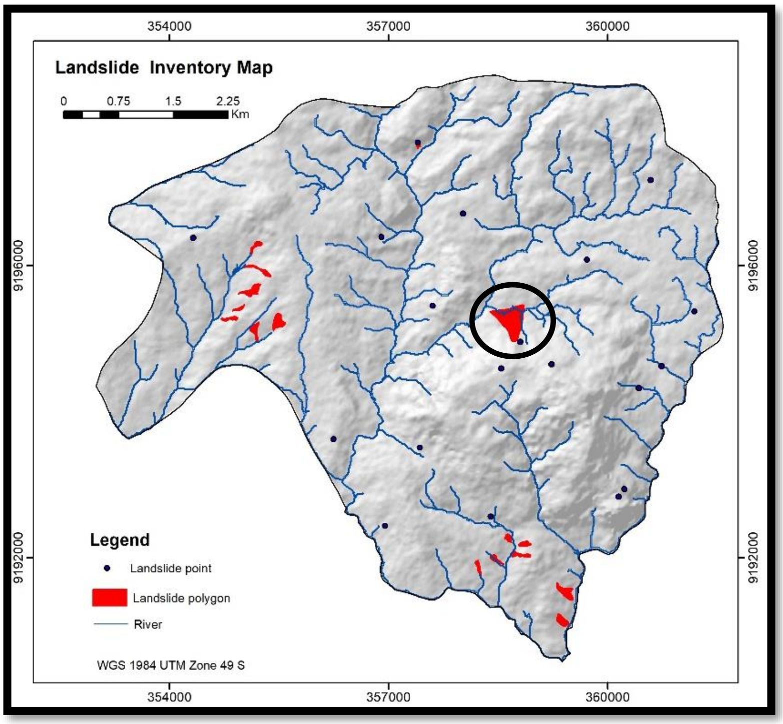


Figure 3-6 The landslide inventory locations in Karangkobar. The red colour indicates the runout acquired from google earth imagery. The black circle showed the largest landslide in 2014.

4. METHODOLOGY

4.1. General Framework

To use a physically based modelling for assessing the slope stability and flood hazard in the study area and to implement it in a Landslide Early Warning System, the following methodology is adopted (Figure 4-1). In general, the study consists of the parameterization of input data for physical modelling in Open Lisem, generation of the homogeneous unit automatically by using r.slopeunits (with DEM as the main input) and use a combination method (with settlement map and slope map as the input), modelling the slope stability and flood in the area by using Open Lisem, integrating the physical model results into the meaningful units, and finally modelling with the rainfall scenarios which leads to develop a local warning levels.

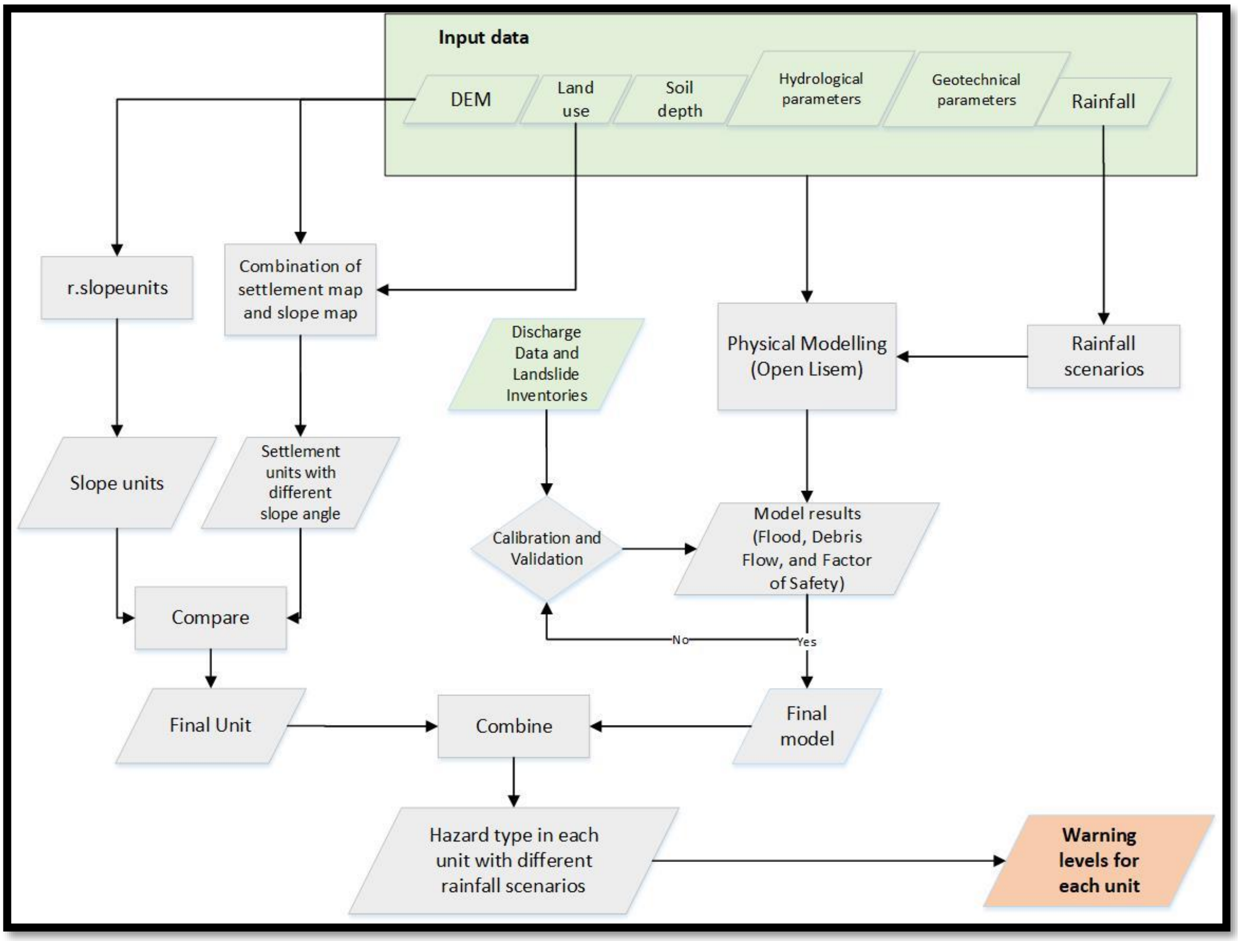


Figure 4-1 The flow chart of the study

The methodology steps will be discussed below in detail. As the development of the methodology had to take into consideration the peculiarities of the case studies, the following paragraphs also include some description for them, as well as the specific description of the steps that were followed for the data preparation.

4.2. Fieldwork and Collection of Data For The Analysis

The main purpose of the fieldwork is data collection, which are data that relevant to the landslide occurrence in the area and data to facilitate the analysis of landslide using physical modelling. The activities consist of:

- Collect the primary data in Bompon, Magelang Regency. These data are soil samples, soil depth, and the landslide inventory. With respect to the latter, landslides were visited inside the area of Bompon and in the extended area in its surroundings. Data for the landslide occurrence date, landslide dimensions, and location were collected. Additionally, information of the type of exposed elements (mainly buildings and rice field) and the damages caused by previous events were also collected.
- Collect the secondary data in Gadjah Mada University (UGM) and Balai Sabo, Yogyakarta, includes landslide inventory, discharge data, and rainfall data.
- Interview the local people about the extent of landslide and flood events in the area, the application of current landslide early warning systems and current landslide risk management.
- Test the soil samples at the UGM laboratory.

The Karangkobar area was not visited during the fieldwork, as mentioned in chapter 3.

The summaries of data that have been collected for both study areas and their source are shown in Table 4-1 and Table 4-2.

Table 4-1 List of data for the Bompon area

Data Type	**Source**	**Resolution**	**Remarks**
Digital Elevation Model	Alos Palsar	12.5 m x 12.5 m	-
Land Use Map	University of Gadjah Mada	-	In shape file
Landform Map	University of Gadjah Mada	-	In shape file
River Map	University of Gadjah Mada	-	In shape file
Road Map	University of Gadjah Mada	-	In shape file
Lithology Map	University of Gadjah Mada	-	In shape file
Landslide inventory	Ulfa (2017)	-	MSc Thesis
Rainfall	University of Gadjah Mada	15 and 30 minutes	There are 4 stations: - 3 Stations recorded from November 2015 to February 2016 - 1 station recorded from March 2014 to July 2017
Discharge Data	University of Gadjah Mada	-	There are 3 discharge measurements, on 21 and 22 January 2016 and 10 February 2016
Physical soil parameters	Field mapping and laboratory analysis	-	2 soil samples, 8 soil depth, and 25 landslide inventories

Table 4-2 List of existing data for the Karangkobar area

Data Type	**Source**	**Resolution/Scale**	**Remarks**
Digital Elevation Model (DEM)	Alos Palsar	12.5 m x 12.5 m	-
Geological map	Condon et al., (1996)	1 : 100,000	-
Land use map	Balai Sabo	1 : 25,000	-
River map	Geospatial Information Agency (BIG)	1 : 25,000	-
Road map	Geospatial Information Agency (BIG)	1 : 25,000	-
Landslide inventory	Arrisaldi (2016)	-	UGM Bachelor Thesis

4.3. Landslide and Flood Hazard Analysis

4.3.1. Generation of The Homogeneous Unit

The subdivision of the homogeneous terrain units was done for both study areas, Bompon and Karangkobar. Two approaches were used to generate the homogeneous unit in this study; (i) by using r.slopeunits approach, and (ii) the combination of settlement and slope approach. The first approach based on the use of the specialized software to generate the slope units automatically, called r.slopeunits (Alvioli et al., 2016). The r.slopeunits software only run on GRASS GIS, an open source GIS (Neteler & Mitasova, 2007). It must be operated within Linux operating system. The DEM is the main input in this software. Before running the model, the input parameters must be defined, which are the flow accumulation area (FA) threshold (in m^2), the minimum surface area (a) for the slope units (in m^2), the minimum circular variance (c) of terrain aspect within a slope unit, a reduction factor (rf), and a threshold value for cleaning procedures. The parameters *a* and *c* are adjusted after parametric analysis for several times whereas the flow accumulation value (FA), a reduction factor (rf), and the cleaning value are kept constant. A sample of the results should be cross-checked against field and image observations to assess the effectiveness of the model in producing realistic slope units using the selected parameters.

The second approach classifies the area into different units based on two criteria: (a) the steepness of the topography and (b) the presence or note of residential areas. To assess the steepness of the topography, the slope map was obtained from the DEM, and it was reclassified into 3 classes, which are low ($< 10^0$), moderate ($10^0 – 30^0$), and steep ($> 30^0$). Next, a raster file of the settlements was prepared based on the land use map. Slope angle classes map was combined with the settlement raster file by using the "cross" command in Ilwis 3.4 as shown in Figure 4-2. The spatial intersection of the slope angle classes and the location of the settlement leads to the different slope angle classes in the settlement units.

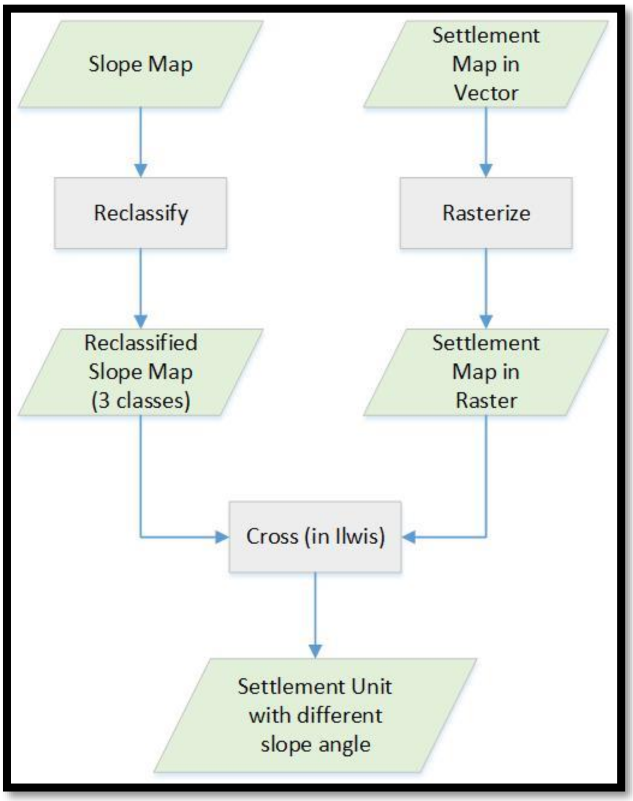


Figure 4-2 Flowchart of the combination of settlement and slope approach

4.3.2. Physical Modelling

This study uses a new Open Lisem (Limburg Soil Erosion Model), an event based-physical model. This new Open Lisem is able to simulate the slope stability and calculate the slope failure height, safety factor, and debris flow height. In order to run the models, it is necessary to have data that includes DEM, soil depth, land use, soil-hydrological parameters (Ksat, porosity, moisture content), rainfall data and the location, geotechnical parameters (cohesion, internal friction angle, and bulk density). All input and output maps for the modelling of Open Lisem were generated in PC Raster environmental modelling software (Karssenberg et al., 2010). It is worth to be noticed, before running the model in Open Lisem, all the input maps must be in the same attributes with the DEM, which are the coordinate, pixel size, and number of rows and columns, otherwise the model cannot be executed.

This study assumed two soil initial moisture conditions for the physical modelling in Open Lisem, namely completely dry and wet condition. Completely dry condition used an initial moisture content 0% while wet condition used an initial moisture content 80% of the porosity. This calculation assumed all areas have a uniform soil initial moisture content. In addition, the simulations were applied by assuming the initial stability in the Open Lisem. Which means, at the beginning of the simulation, everywhere is stable, and the failure is started soon after rain.

Once the physical modelling has been generated, then the model results must be validated with the landslide inventory. The last simulation is the physical modelling with different rainfall scenarios and combined with the homogeneous units in order to know what hazard types exist in each unit, and eventually may be use to develop an early warning system (see section 4.6). In order to do that, the model results must be reclassified based on the degree of the hazard. The safety factor map results were reclassified into 3 classes, unstable (SF < 1), critical (SF 1 – 1.5), and stable (> 1.5). The debris flow and the flood map results used the same classification since they referred to the depth. They were reclassified into 3 classes, low (< 0.5 m), moderate (0.5 m – 1 m), and high (> 1 m)

4.4. Parameterization of The Input Model For Physical Modelling

In the following sections, a detailed analysis is provided for the preparation of the data to be used in Open Lisem. The script for generating the input maps used in PC Raster can be seen in annexes 4.

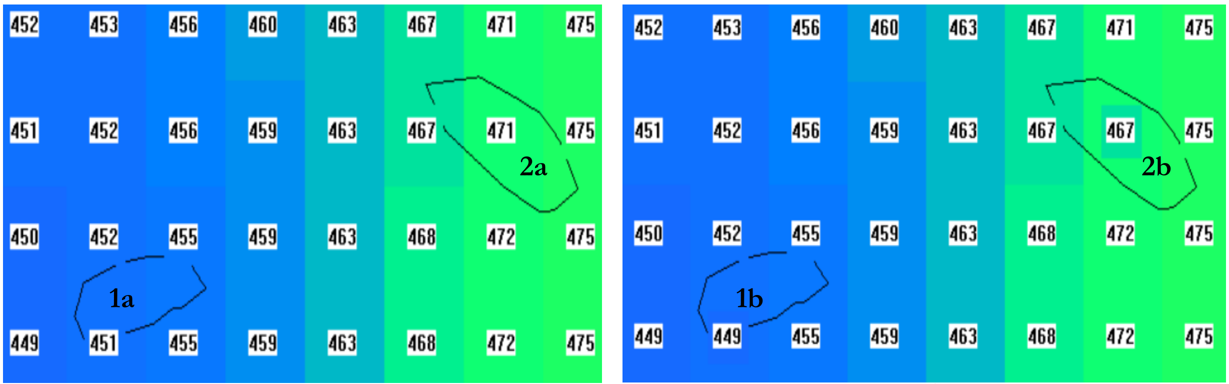
4.4.1. Digital Elevation Model

Digital Elevation Model (DEM) is a basis data in physical modelling. DEM derivatives are slope angle, elevation, curvature, aspect, and local drain direction (ldd). For this study, a DEM was obtained from ALOS PALSAR with resolution 12.5 m, which was downloaded for free through website https://vertex.daac.asf.alaska.edu/ (ASF DAAC, 2017). This DEM is used to visualize the study area and as an input parameter for hydrology and slope stability modelling in Open Lisem. The DEM was also used as the primary input in generating automatic slope units in r.slopeunits.

As shown in Figure 4-3, the landslide type in Bompon is shallow landslides in cut slopes with a relatively small area. Only one landslide is categorized as a deep-seated landslide which has the most extensive area, about 8000 m^2 (see Figure 3-5). These areas were digitized manually by taking into account the landslide dimension based on the field observation and google earth imagery. Those small landslides cannot be identified using the google earth due to the dense vegetation cover, except the only most significant landslide in the area.

Figure 4-3 Landslide condition in Bompon area

Considering the small landslides dimension in the area and the difficulty in identifying them by using the 12.5 m spatial resolution of DEM, the pixel value of the DEM where the landslide at cut slope occurred was changed to make the DEM more realistic. The pixel modification was done in Ilwis 3.4. To do so, first, made the landslide polygon which was considered as cut slope. After that overlaid the cut slope polygon layer on the DEM layer. As shown in Figure 4-4 (a), the boundaries of the cut slope (1a and 2a) are overlaid over the DEM, and there are the elevation values within those boundaries. The pixel value could be modified manually by using edit layer and choose DEM layer (as this is the layer that should be modified), after that "double-click" to the pixel that should be modified. The pixel value can be changed by taking into consideration the lowest elevation in the surrounding of the cut slope boundary (1b and 2b), as shown in Figure 4-4 (b).



452	453	456	460	463	467	471	475
451	452	456	459	463	467	471	475
450	452	455	459	463	468	472	475
449	451	455	459	463	468	472	475

(a)

452	453	456	460	463	467	471	475
451	452	456	459	463	467	467	475
450	452	455	459	463	468	472	475
449	449	455	459	463	468	472	475

(b)

Figure 4-4 Modification DEM pixel value in Ilwis for Bompon area. (a) DEM original before modification and (b) DEM after modification

After modifying the pixel values of the DEM, then the new modified DEM was used to generate the slope angle map. Once the slope map has been created, the result was compared to the slope map derived from the original DEM. The results of the slope map before and after modification are shown in section 6.1.1

4.4.2. Rainfall Data

Four rainfall stations are located within Bompon catchment, namely Kalisari, Bompon, Kuaderan, and Wonogiri. The stations have 15-minutes and 30-minutes temporal resolution. Another rainfall station, namely Ngasinan, is located outside the study area with a distance approximately of 1.5 km, with daily rainfall records (Figure 4-5). Kalisari station recorded the rainfall every 15 minutes, and it was started from March 2014 to July 2017. However, the rainfall was not recorded for all the period. There were some missing data, and some of them were not fully recorded in a month. In Bompon station, the rainfall was recorded every 30 minutes, and it was started from October 2015 to February 2016. Similar to Kalisari station, some of the data were not recorded fully in one month. The Kuaderan and Wonogiri stations provided rainfall information from October 2015 to February 2016 and from July 2015 to February 2016, respectively. Both of these stations recorded the rainfall every 15 minutes. These stations also do not have the complete rainfall record in a month.

For Karangkobar area, the available daily rainfall data are from Banjarnegara station (for December 2014) which is located around 0.5 km outside the area (Figure 4-5), and the satellite rainfall data from Huffman et al., (2014). The spatial resolution of the satellite rainfall data is 0.1^0 or around 11 km, and the temporal resolution is 30 minutes. The data was downloaded for the rainfall on December 2014 which corresponded to the occurrences of the landslide in the area. However, the amount of rainfall for the date of the occurrence of landslide events derived from the satellite is much lower than ground station (rainfall from GPM 23.6 mm and Banjarnegara station 101.8 mm).

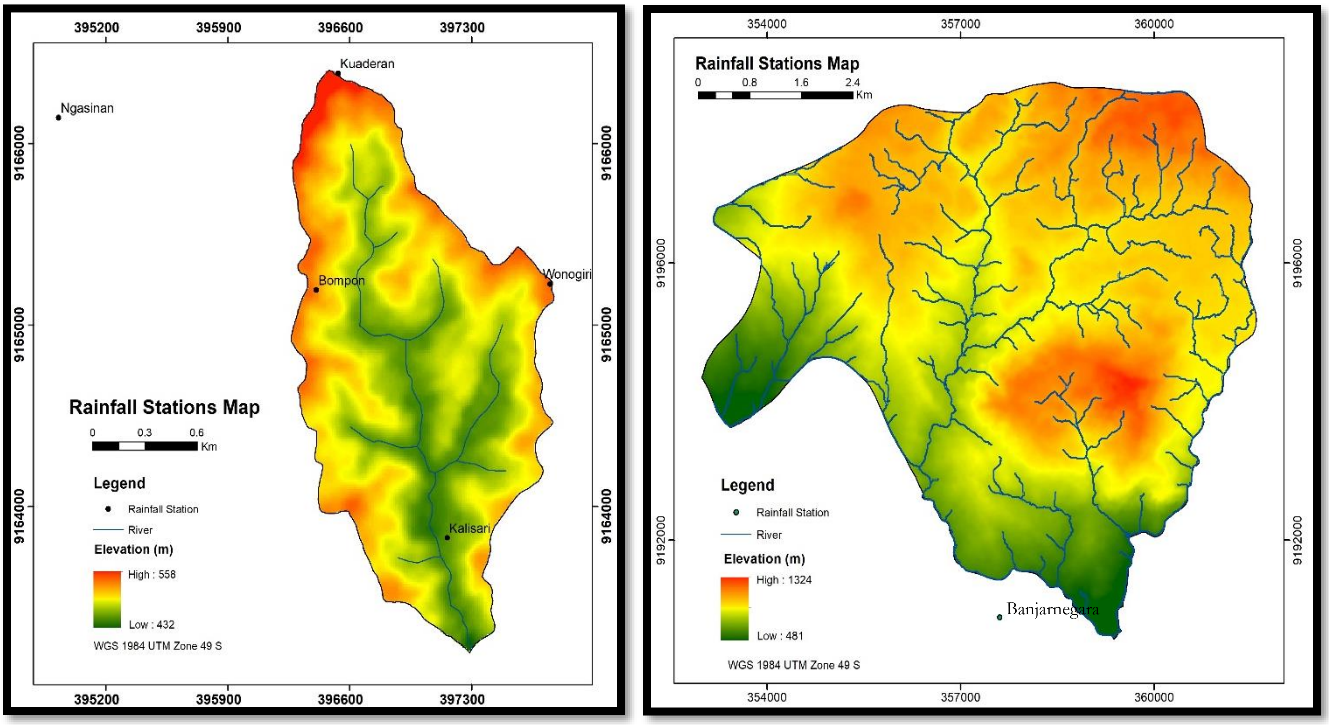
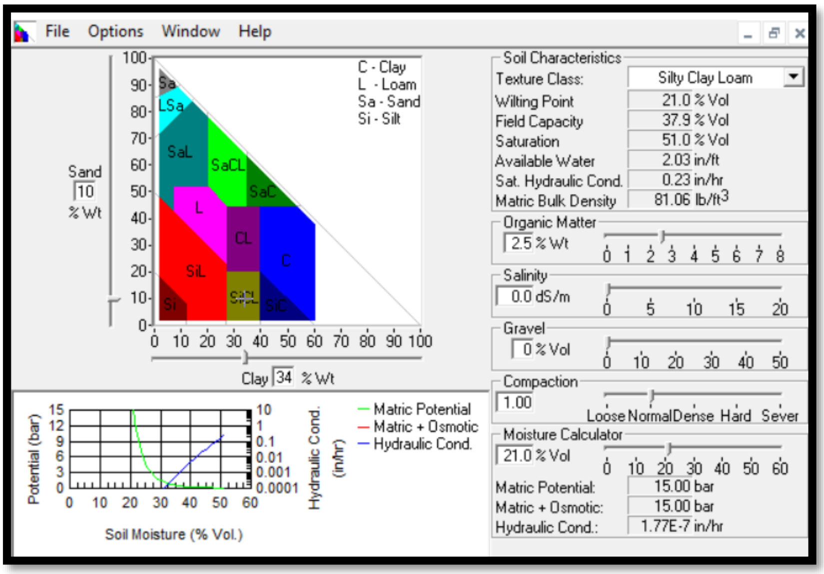


Figure 4-5 Rainfall Station Locations in Bompon (left) and in Karangkobar (right)

4.4.3. Soil Texture

For the Bompon area, the soil texture class obtained from soil texture percentage of clay, sand, and silt, in the attribute of the landform map that was provided by Geography Faculty of UGM. The soil texture classes were calculated by using pedotransfer functions of Saxton & Rawls (2006) (Figure 4-6).



Sand 10 % Wt

Clay 34 % Wt

Texture Class: Silty Clay Loam
Wilting Point 21.0 % Vol
Field Capacity 37.9 % Vol
Saturation 51.0 % Vol
Available Water 2.03 in/ft
Sat. Hydraulic Cond. 0.23 in/hr
Matric Bulk Density 81.06 lb/ft3
Organic Matter 2.5 % Wt
Salinity 0.0 dS/m
Gravel 0 % Vol
Compaction 1.00
Moisture Calculator 21.0 % Vol
Matric Potential: 15.00 bar
Matric + Osmotic: 15.00 bar
Hydraulic Cond.: 1.77E-7 in/hr

Figure 4-6 A pedotransfer function to calculate the soil texture and soil-hydrology parameters

In addition, the soil-hydrology parameters, which are hydraulic conductivity (Ksat) and porosity, and the soil-geotechnical parameters, which are cohesion, internal friction angle, and bulk density, obtained from the laboratory analysis and literature. However, only soil-hydrology parameters were analysed in the laboratory of Geography Faculty, UGM. The soil-geotechnical parameters were not available; then they were taken from Geotechdata (2008) (http://www.geotechdata.info). The selection of these parameters was based on the soil textures in the study area, and it is discussed in section 6.1.3.

A similar method was applied for acquiring the soil parameters in Karangkobar. Due to the unavailable data for soil textures, soil-hydrology, and soil-geotechnical parameters in the area, these data were obtained from the literature. The soil textures were obtained from Hengl et al., (2017) (https://soilgrids.org) by taking into account the sand and clay content, coarse fragment, and organic matter, for the next analysis to find out the soil-hydrology parameters. The spatial resolution of the original soil texture map was too coarse, about 250 m, then it was resampled to 12.5 m resolution by using the bilinear technique, in order to have the same spatial resolution with the DEM. Furthermore, the soil-hydrology parameters were calculated using pedotransfer functions of Saxton & Rawls (2006). Also, the soil-geotechnical parameters in the area were obtained from Geotechdata (2008) (http://www.geotechdata.info) which referred to the soil texture derived from pedotransfer functions.

4.4.4. Soil Depth

Soil depth was measured during the fieldwork by finding locations where the difference between fresh soil or weathered soil, and bedrock could be distinguished. The soil in the area is very thick, which was impeding finding such locations. Eight locations could be found for measuring soil depth, particularly along small roads or rivers.

Furthermore, since only small parts of the soil thickness could be measured and be found in the location, then to obtain the thickness for all the catchment area, the interpolation technique was applied by using the inverse distance weighting method. The method for predicting soil depth in a small catchment has been used successfully by Kuriakose et al., (2009). The model equation used in the study is:

SD = $a + b \ast DEM + c \ast Cd + d \ast S + e \ast C$ ……………………………………………………………Equation 2

where SD is simulated soil depth (m), a is the intercept, b,c,d, and e are the calibration constants (-) derived from statistical analysis, Cd is the distance to the nearest channel (m), S is the slope of the surface (m m^{-1}), and C is the profile curvature of the surface (m^{-1}). All the values of the interception and calibration constants are shown in Table 4-3.

Table 4-3 Values of interception and calibration constants of soil depth model

	a	b	c	d	e
Value	4.5	- 0.0008	- 0.0076	- 0.7	79

On the other hand, due to unavailable data for soil depth in Karangkobar, then it was acquired from Hengl et al., (2017) (https://soilgrids.org) with a limited level of detail. The soil depth map was downloaded for the maximum depth to 2 m. The spatial resolution of the soil depth map was 250 m, therefore in order to have the same resolution with other input maps, it was resampled to 12.5 m by using the bilinear technique.

Critical Soil Depth

The critical soil depth was calculated as a second alternative for the soil depth to be used in the physical modelling for Karangkobar area. It determines the soil depth for which the stability of the slope is critical. To do that, the equation 1 in chapter 2 was used to find out the critical soil depth. The new equation to find out the soil depth is:

z' = $c \;/\; (Fos \ast \gamma \ast sin\beta \;-\; \gamma \ast cos\beta \ast \tan\phi')$………………………………………………………………………Equation 3

For this calculation the safety factor value is 1.1 and z' is the critical soil depth (m) that corresponds to the safety factor 1.1. The simple calculation from the equation 3 was calculated in Excel. In addition, it also could be calculated in Arc Map by using "raster calculator". However, this critical soil depth calculation assumed a homogeneous of soil cohesion and internal friction angle.

4.4.5. Land Use and NDVI

For both areas, Bompon and Karangkobar, the land use parameters and NDVI were not available. Consequently the land use parameters that were used for modelling, that are the Manning's roughness coefficient (n) and surface roughness, were taken from LISEM Manual (2016) by taking into consideration the land use types (see Figure 3-2). The same land use parameters were utilized for both study areas for the physical modelling in Open Lisem (Table 4-4).

Table 4-4 Land use parameters for both study areas

No	Land Use	Manning's n	Surface Roughness (cm)
1	Dry cultivated land	0.03	0.7
2	Settlement	0.05	0.5
3	Mixed plantation	0.1	1
4	Rice field	0.05	0.1
5	Shrub	0.1	0.5
6	Water body	0.05	0.1

The Normalized Differential Vegetation Index (NDVI) was obtained from USGS (2015), and it was required to obtain the Leaf Area Index (LAI) and vegetation cover value. The NDVI was derived from Landsat 8 OLI and then resampled to 12.5 m.

The next step was to calculate the vegetation cover by using a linear scale between the minimum and maximum NDVI value and lastly the LAI value could be achieved from the empirical equation below (Choudhury et al., 1994) :

$$LAI = \frac{\ln(1\text{-vegetation cover})}{-0.4} \quad \text{……Equation 4}$$

4.5. Model Calibration and Validation

The calibration of the hydrological model was applied only for the Bompon area, due to the unavailable discharge data in Karangkobar. However, the calibration was only used for hydrological modelling by comparing the model result and the available measured discharge data on 10 February 2016. The hydrological model was considered calibrated was the runoff fraction in the model which is the percentage of the discharge and the rainfall, gave the closest value to the runoff fraction measured. Once it was done, the calibration of hydrology parameters was kept for the modelling the slope stability.

In Open Lisem, the calibration also may be done for slope stability modelling, by adjusting the slope stability parameters, which are cohesion, internal friction angle, and soil depth. After obtaining the fittest calibration parameters, the slope stability results were validated with the landslide inventories, to see how many landslides are predicted well located in the unstable area. It is necessary to do the validation in order to know whether the model gives under-estimation or over-estimation results. For this study, the validation was done for both study areas, by using back validation of the landslide events on 21 December 2011 in Bompon and on 12 December 2014 in Karangkobar.

4.6. Developing a Local Landslide Early Warning System

To establish a local landslide early warning system, it is necessary to know the location which has more chance to be affected by the hydro-meteorological hazards. The slope units without further processing also do not adequate to be used for a hazard assessment, because these units have a more significant area than settlement units and do not have a meaningful function in term of early warning. Therefore, the settlement is the useful unit to deliver the warning because it has a high density of people.

Once the segmentation of the settlement unit has been generated, and the physical modelling has been validated with the landslide inventory, then the same physical modelling was applied in Open Lisem, but with different rainfall scenarios. The result of the simulation with rainfall scenarios is combined with the settlement units to investigate the hazard types for each one of the three rainfall scenarios. Before combining the hydro-meteorological hazards, it is necessary to reclassify each hazard. The classification of the hazard is described in section 4.3.2.

Each unit has a unique code result in from the combination of model result and settlement units. For example, unit ID “Critical*Moderate*15” means that the settlement unit no. 15 at moderate slope angle is located in a critical area with the Safety Factor 1 – 1.5 (Figure 4-7). The illustration from Figure 4-7 below shows that in one settlement unit with the number 15 is separated by different slope angle class and hazard class. For this case, the settlement unit with the highest hazard class is prioritized to be given the warning.

The application of different rainfall scenarios in the simulation will generate a different level of hazard in each settlement unit. Theoretically, the more rainfall is employed in the simulation, the more settlement units are affected by the hazard.

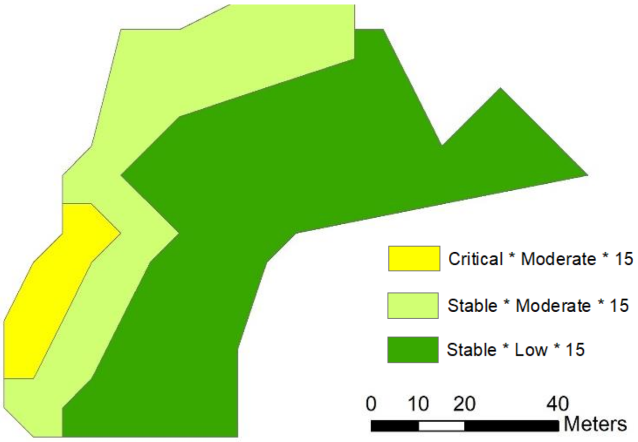


Figure 4-7 An example to illustrate the combination of the settlement unit with the safety factor

Once the rainfall in scenario 1 is reached, the warning level is issued by the local authority to the settlement units with the highest hazard class to be aware. Furthermore, if the threshold for rainfall scenario 2 is exceeded, then the warning level is increased from "awareness" to "increase the awareness". At this scenario, the settlement units which are affected by the hazard in scenario 1 will have an extended hazard area as well as the hazard level. Therefore, the action for inspecting the surrounding area is needed to check whether there is a small landslide occurs or not. If there is evidence of the occurrence of a small landslide in that particular settlement units, then the action to prepare the evacuation should be performed. For scenario 3, the evacuation should be done. Given a very high rainfall depth in scenario 3 will produce more settlement units to be affected by the hazard as well as the increasing level of hazard. The propose of developing a local landslide early warning system is shown in Table 4-5

Table 4-5 A local LEWS based on the rainfall scenarios (adopted from SafeLand, 2012)

Scenario	Warning Level	Actions
I	Awareness	No action
II	Increase awareness	- Inspect the area - If there is a report of the occurrence of small landslide, prepare for evacuation
III	High Hazard	Evacuation

5. GENERATION OF THE HOMOGENEOUS UNIT

This chapter is divided into two section. Section 5.1 described the result of slope units using the r.slopeunits software, and section 5.2 described the result of the intersection between slope map and settlement map.

5.1. Assessment of Homogeneous Unit by Using r.slopeunits

The slope units model for Bompon area resulted in 558 units (Figure 5-1 a). The best parameters for the slope units in the area were defined as follow: flow accumulation (FA) threshold 10000 m^2, the minimum area (a) 1000 m^2, the circular variance (c) 0.35, the reduction factor (rf) 10, and the threshold for cleaning procedures (r) 50 m^2. These values were changed several times to obtain the fitted slope units for the area.

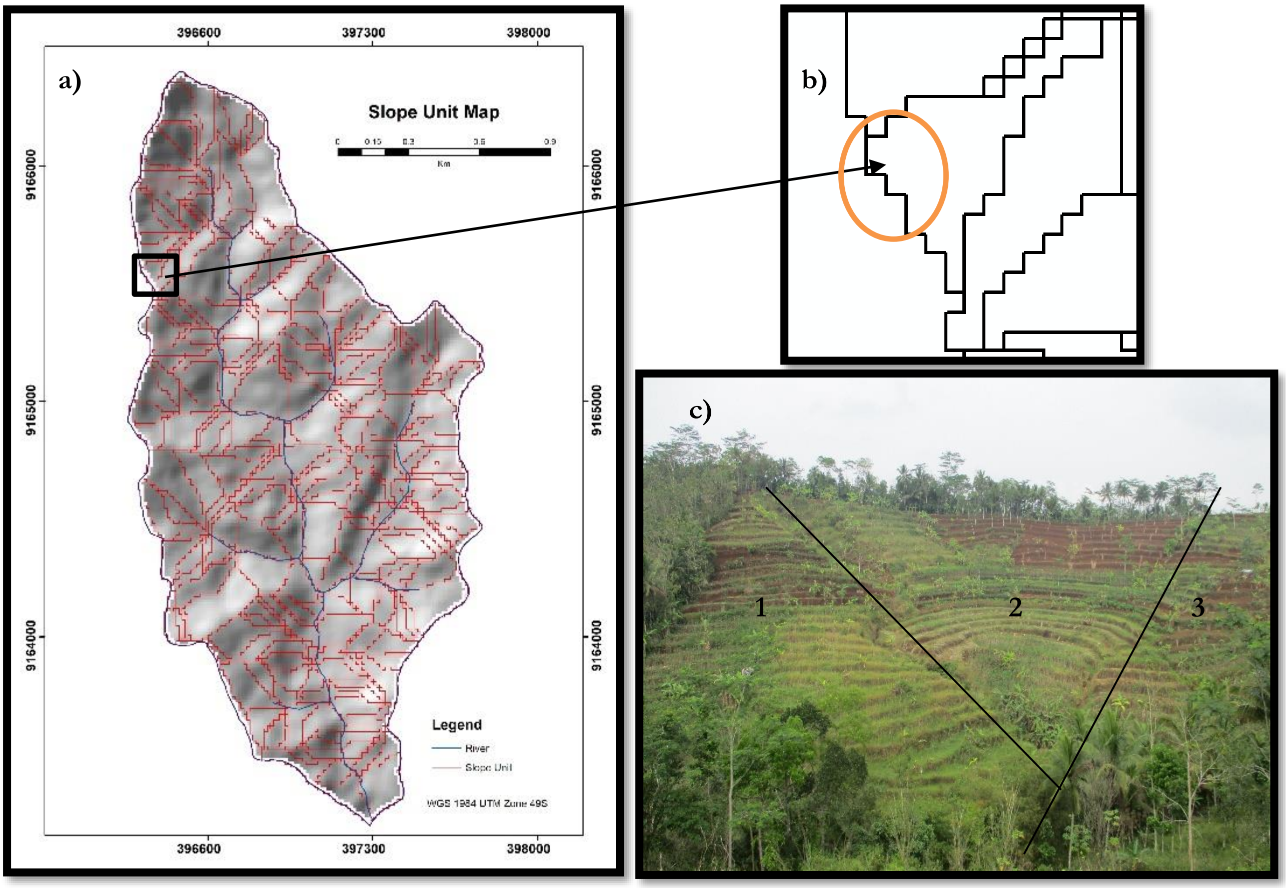


Figure 5-1 Slope units in Bompon (a). A detail view of the slope units (b). The slope unit that is located in an orange circle found in the field, where the number (1, 2, 3) shows the segmentation of the slope units (c).

However, the result of slope units in the area did not seem realistic. As can be seen in Figure 5-1 (b), it displays the slope units in detail, and the slope is segmented to the several slope units. Compared to the segmentation that was found during fieldwork which was located within the orange circle in Figure 5-1 (b) the model only segmented the slope into one slope unit, but in the field, as shown in Figure 5-1 (c), the slope is subdivided into 3 slope units. This is possibly due to the fact that the slope angle variation in the DEM is not high. The variation of elevation from 432 m to 558 m and only 126 m difference between the highest elevation and the lowest elevation, and also the slope angle variation from 0^0 to 30.21^0. It has to be noted that in the field, higher slope angles were also observed which are not represented in the DEM due to its low resolution.

The slope units generation in Karangkobar resulted in 1411 units (Figure 5-2). The best parameters for the slope units in the area were defined as follows: flow accumulation (FA) threshold 100000 m^2, the minimum area (a) 1000 m^2, the circular variance (c) 0.20, the reduction factor (rf) 10, and the threshold for cleaning procedures (r) 500 m^2.

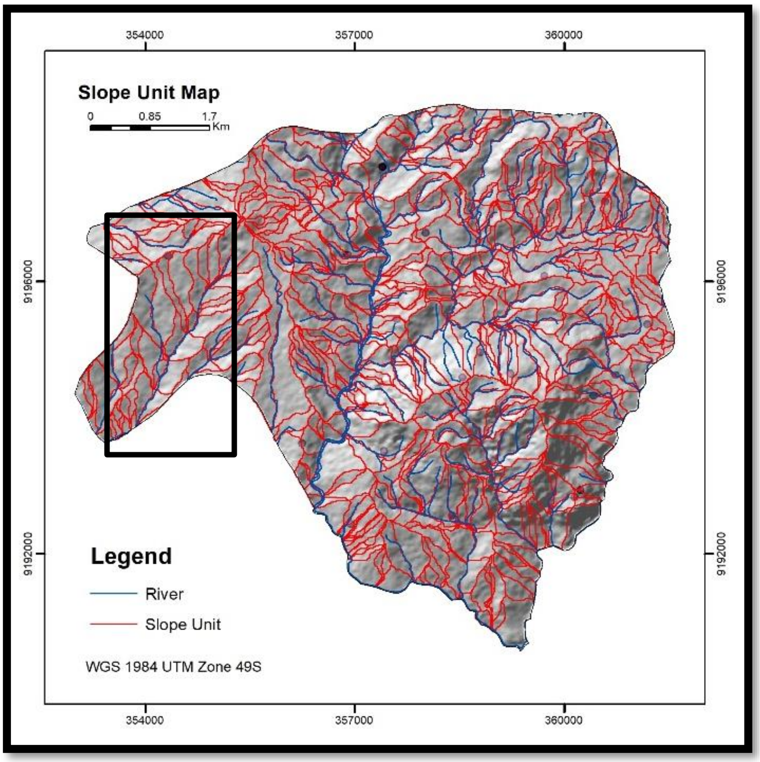


Figure 5-2 Slope units result in Karangkobar. A black square indicates the location to compare the slope units with google earth imagery

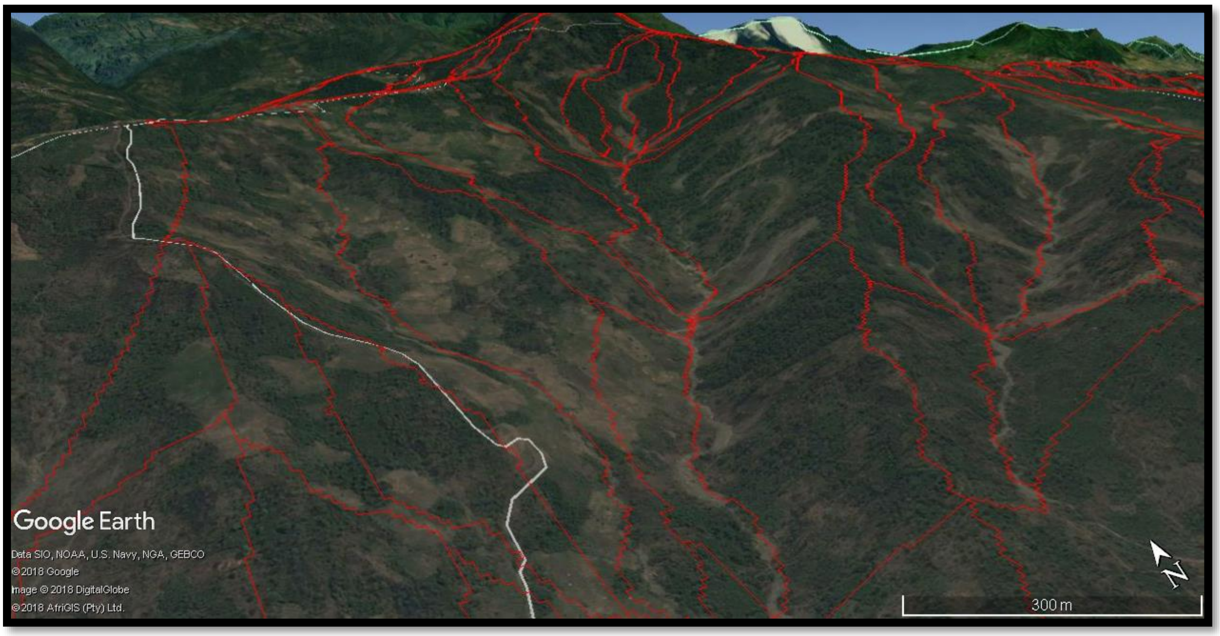


Figure 5-3 Slope units view of Karangkobar in google earth imagery

The segmentation of the slope units in Karangkobar showed more realistic result than in Bompon. As can be seen in Figure 5-3, the slope was successfully segmented by the model. This might be affected by the variation of elevation and slope angle in the area are higher than Bompon area, with elevation ranges from 481 m to 1324 m, and slope angle ranges from 0^0 to 64.4^0.

All the parameters for generating the slope units as mentioned above depend on the study area and the available DEM. The larger the area, the higher the threshold of flow accumulation (FA) used. Also, the use of flow accumulation (FA) threshold in this software has the function to subdivide the slope based on the drainage lines. Furthermore, the minimum area (a) means the minimum size of the area considered to be segmented as a unit and the circular variance (c) has a function to control the aspect. Low *c* value will result in more homogeneous unit, and high *c* value will generate more heterogeneous unit.

Based on the comparison result between the slope units from the model and the image as shown in Figure 5-1 and Figure 5-3, it can be concluded that the generation of slope units automatically by using r.slopeunits is better for hilly areas with a high variation of elevation and slope angle.

5.2. Assessment of Homogeneous Unit by Using a Combination of Settlement and Slope Angle Classes

Considering the slope units result which was unrealistic in Bompon, then an alternative approach to generate homogeneous unit was performed. Such approach was to combine of two raster maps: a) the slope angle map and b) the residential area map. This resulted in the units of settlement area with different slope angle (Figure 5-4). As mentioned in the previous chapter, the slope angle was reclassified into 3 classes, low (< 10^0), moderate (10^0 – 30^0), and steep (> 30^0). The slope angle variation in Bompon area is not as high as in Karangkobar, thus only 2 classes of slope angle exist in Bompon. The generation of settlement units in Bompon produced 182 units which are classified as settlement units at low slope angle and settlement units at moderate slope angle. On the other hand, the total settlement units in Karangkobar is 315 units, with 3 classes, settlement units at low slope angle, settlement units at moderate slope angle, and settlement units at steep slope angle.

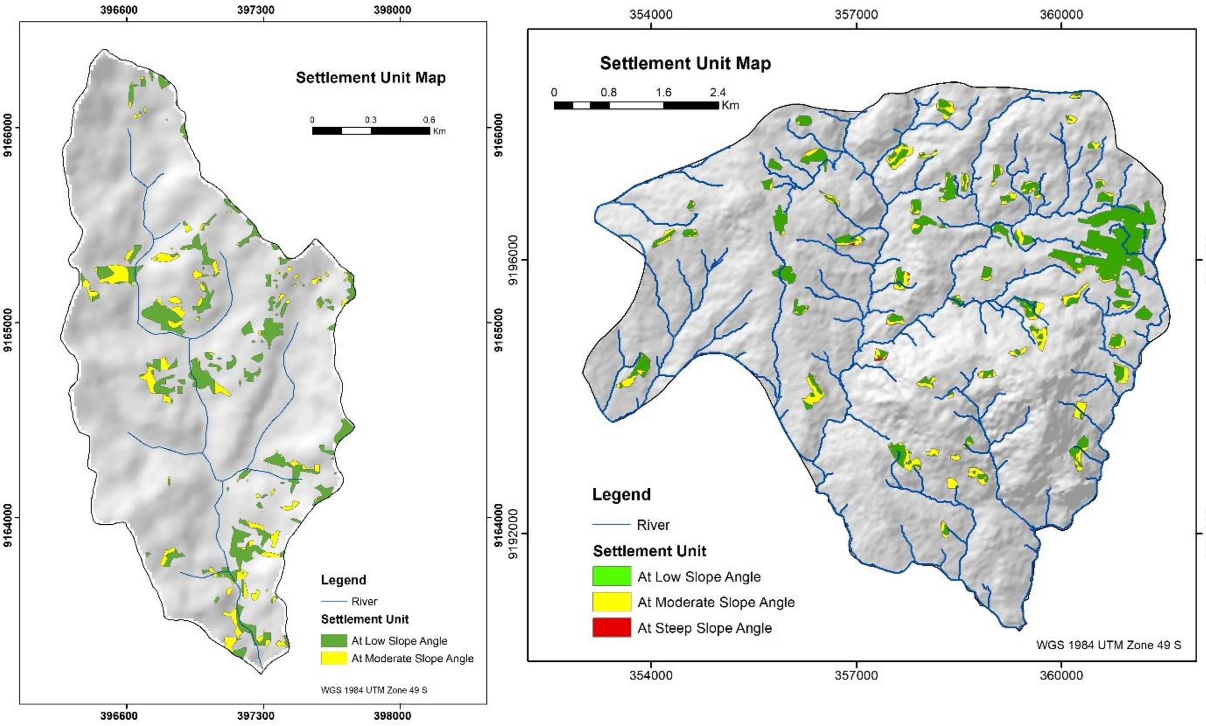


Figure 5-4 The settlement units with different slope angle for Bompon (left) and Karangkobar (right)

It is worth to be noticed that in terms of Early Warning System, the residential areas are a priority in delivering the alert because they are places of high people density. Therefore, the units where human activity takes place dominantly, in this case, the dwelling and the surrounding area, were considered as the meaningful units for further analysis. These units will be combined with the physical modelling results in order to assess the hazard occurrences for each settlement unit and eventually lead to giving the warning for which settlement unit is more dangerous at a given rainfall scenario.

As shown in Figure 5-4, the settlement units for both study areas are dominantly located at the low slope and followed at the moderate slope. It is only in Karangkobar area where there are settlement units at the steep slope. In fact, there are several houses located on a steep slope in Bompon. However, the limited resolution of the DEM used in generating the slope map for this area, causes an underestimate slope compared to the reality. The percentage coverage units for both study areas are shown in Table 5-1.

Table 5-1 Settlement units percentage for both study areas

Settlement unit in Bompon	Slope class			Total
	Low ($0^0 - 10^0$)	Moderate ($10^0 - 30^0$)	Steep ($> 30^0$)	
Area (m^2)	197,346	86,564	-	283,910
Percentage (%)	69.51	30.49	-	100
Settlement unit in Karangkobar				
Area (m^2)	2,007,189	888,751	11,407	2,907,347
Percentage (%)	69.04	30.57	0.39	100

6. PHYSICAL MODELLING USING OPEN LISEM

The Open Lisem was used to model the hydro-meteorological hazards (slope stability and flood) for both study areas, Bompon and Karangkobar. In the following sections, detailed results are presented for the data and the physical modelling in Open Lisem.

6.1. Data Analysis and Application To The Study Area

6.1.1. Digital Elevation Model Analysis

The Digital Elevation Model is an essential data for slope stability modelling in Open Lisem. To analyse the quality of the DEM, the slope angle derived from the DEM was compared to the slope angle in the field. The variation of slope angle derived from the DEM ranges from 0^0 to 30^0, but in fact, the slope angle in the field is more than 30^0 and even almost has a very steep slope angle, especially the location where cut slopes exist. From the total of 25 identified landslide locations in this area, there are 13 landslides in cut slopes, and the remaining 12 landslides occurred at natural slopes, next to the rice fields, shrubs, and mixed plantation.

There were 5 locations where the slope could be measured in the field. The differences of slope angle measured in the field and slope angle derived from DEM are shown in Table 6-1. It indicates that the low resolution of the DEM results in an intense smoothening effect on the calculated slope angle from the DEM.

Table 6-1 Differences of slope angle measured and model

No	X	Y	Slope (measured) (^{0})	Slope (model) (^{0})
1	396617	9164666	20	11.31
2	397481	9164459	26	13.67
3	396963	9163858	32	14.57
4	397204	9164451	33	13.13
5	397469	9164477	38	7.43

As mentioned before, in the study area of Bompon, the landslide types are mainly cut slopes where they are hardly identified by the available DEM used in the model. In addition, the slope angle from the DEM is lower than the slope angle in reality. An attempt to make more realistic DEM had been done by modifying the pixel value of the DEM where the cut slope occurred. However, the resulting of modified DEM did not give a more realistic slope, for example, before modifying the DEM, the maximum slope angle was $30.22^{0,}$ and after modifying the DEM, the slope angle becomes 31.70^0 (Figure 6-1). Considering the modifying results which had no significant difference, then it was decided to use the original DEM for modelling in Open Lisem.

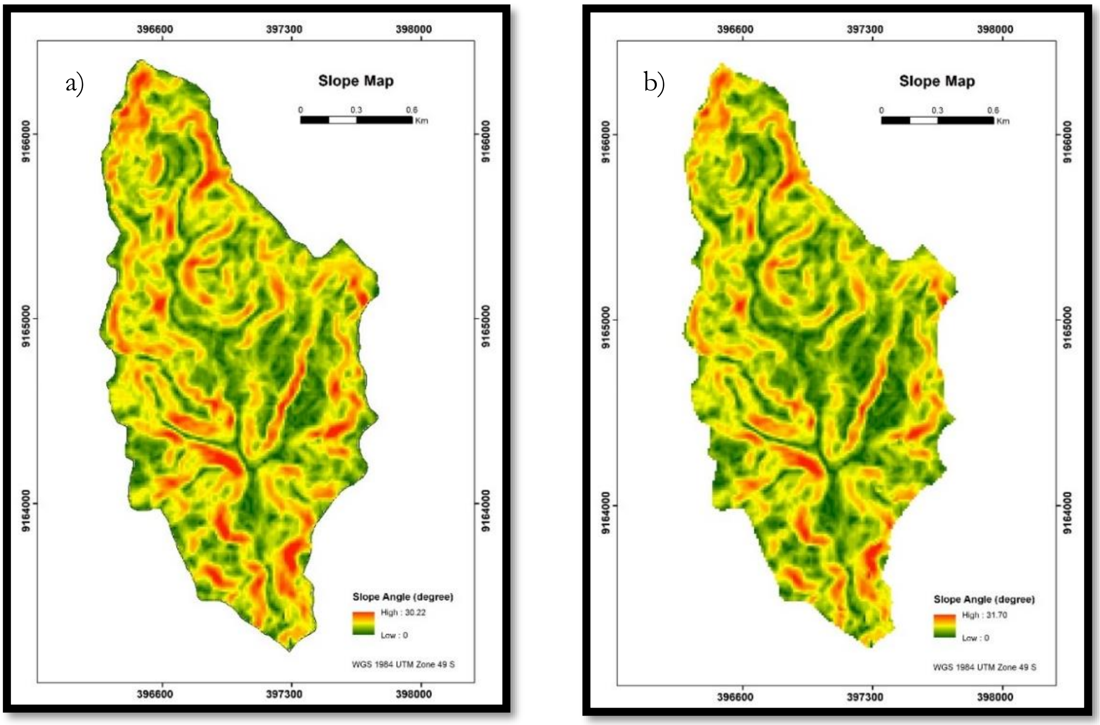


Figure 6-1 Slope map before modifying the DEM (a) and Slope map after modifying the DEM (b)

6.1.2. Rainfall Scenarios for Landslide and Flood Hazard Analysis

As mentioned in section 4.4.2, a complete rainfall data between the 4-rainfall stations within the study area was from October 2015 to February 2016. However, only Kuaderan and Wonogiri stations showed a good correlation between the other rainfall stations (Kalisari and Bompon) and these stations had more complete data during this period (Figure 6-2). As these stations had the similar total amount of rainfall as well as the rainfall duration, it was decided to use the rainfall data from these stations for modelling to calibrate the discharge. In addition, the Kuaderan and Wonogiri rainfall stations had the rainfall data which corresponded to the discharge measurement in the area (21 and 22 January 2016 and 10 February 2016).

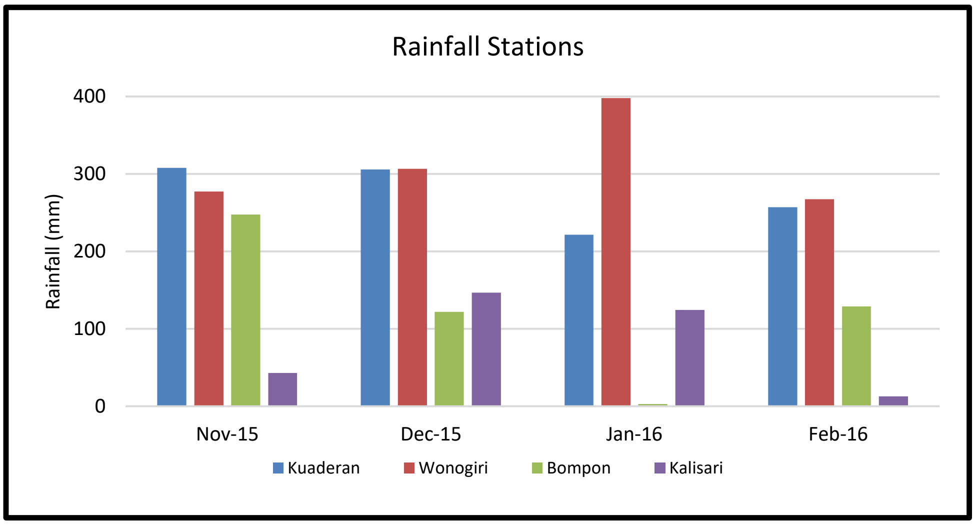


Figure 6-2 Comparison of total rainfall in a month for all stations in Bompon catchment

The available discharge data was calculated every 10 minutes. To calibrate the hydrology model, the rainfall of 10 February was used instead of the measurements on 21 and 22 January, given its high amount (higher than the measurements of 21 and 22 of January, when no landslide occurred).

The landslide events that occurred in Bompon was in 2011. Unfortunately, the 4 rainfall stations within this area which have a high temporal resolution did not have the rainfall record for that year. Because they were installed in 2014 (based on the first record of Kalisari station). Therefore, the daily rainfall record from Ngasinan station was used for simulating the slope stability for the landslide event in 2011.

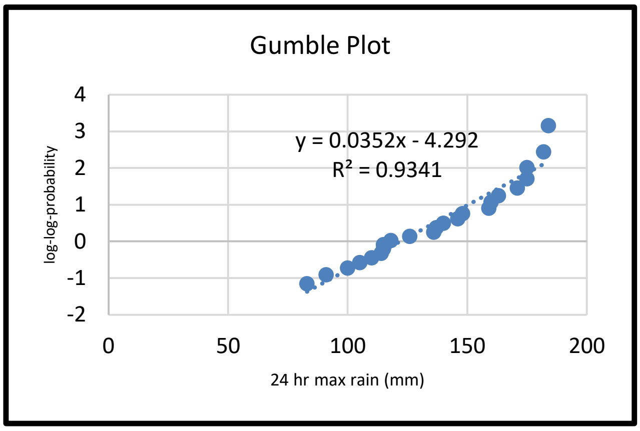
The Ngasinan station recorded daily rainfall from 1990 to 2015, and it was used to find out the extreme rainfall values in this long-term data. In 2006 and 2007 there was no rainfall record, and in 2008 the rainfall was recorded only 5 months, thus these 3 years were neglected for further analyzing. To calculate the expected extreme rainfall in the area, the first step was to choose the maximum rainfall value for each all the sampling years (Table 6-2).

Table 6-2 The 24 hr max rainfall at Ngasinan station (in mm)

Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
1990	34	51	39	-	83	59	52	41	13	40	58	74
1991	175	124	94	119	0	0	0	0	0	16	53	80
1992	97	93	119	152	117	37	22	171	32	112	91	80
1993	78	71	115	75	51	43	0	25	0	6	102	91
1994	130	47	136	81	49	4	0	0	0	15	48	56
1995	67	173	79	125	54	37	42	4	0	140	184	46
1996	68	86	148	23	3	2	8	4	10	50	56	115
1997	83	163	29	43	47	20	0	0	0	2	6	55
1998	76	87	88	73	76	175	62	28	36	105	90	66
1999	146	87	125	131	35	24	15	36	6	59	95	78
2000	100	61	64	90	47	30	0	2	23	65	80	100
2001	95	44	76	109	50	41	56	3	47	114	70	56
2002	80	-	56	-	-	23	0	0	0	9	126	92
2003	127	102	182	37	78	16	0	0	0	0	83	100
2004	80	105	94	80	39	6	50	0	15	27	60	91
2005	56	110	77	84	9	36	23	25	-	-	-	-
2006	-	-	-	-	-	-	-	-	-	-	-	-
2007	-	-	-	-	-	-	-	-	-	-	-	-
2008	-	-	-	-	-	-	-	0	0	94	85	68
2009	73	59	33	91	58	45	0	0	6	20	73	67
2010	86	75	84	0	137	80	95	48	77	59	48	78
2011	56	159	55	42	60	0	0	0	0	10	50	75
2012	160	75	75	60	50	3	0	0	0	13	113	75
2013	92	73	69	88	60	40	40	0	0	15	25	140
2014	75	104	51	78	24	84	45	0	0	0	115	92
2015	106	118	53	116	27	5	0	0	0	0	30	45

Remarks:
- : No record
0 : No rainfall

Next, in order to know the extreme rainfall event, then from the Table 6-2 was analyzed by using the Gumbel distribution. The Gumbel assumes a double logarithmic relation between the maximum daily rainfall and the return period, and the return period is the inverse of the probability. Based on the equation from the Gumbel plot, then the maximum rainfall for the specified return period could be calculated (Figure 6-3).



T(year)	PR (=1/T)	PL (=1-PR)	Y = -ln(-ln(PL))	Max mm rain
2	0.5	0.5	0.366513	132
5	0.2	0.8	1.49994	165
10	0.1	0.9	2.250367	186
15	0.07	0.93	2.67375	198
20	0.05	0.95	2.970195	206

Figure 6-3 Gumbel analysis of Ngasinan Station (left). The corresponding return period (T) and max 24 hr rain (mm) (right)

Finally, design storm was made for hazard analysis and generating the rainfall distribution. To design the storms for hazard analysis, in this study used the intensity-duration-frequency curves or IDF curves at Semarang station, Indonesia (International Hydrological Programme, 2008) (Figure 6-4). These IDF curves provide the amount of rainfall (in mm) for each return period. Therefore, the design storm has to correspond to a particular rainfall amount and its duration for each return period. The design storm can also be used to find out the rainfall duration by disaggregating the daily rainfall into a given minute time steps (i.e., 5, 10, 15, etc.). The last step was to create the alternating block method to make a symmetrical design storm.

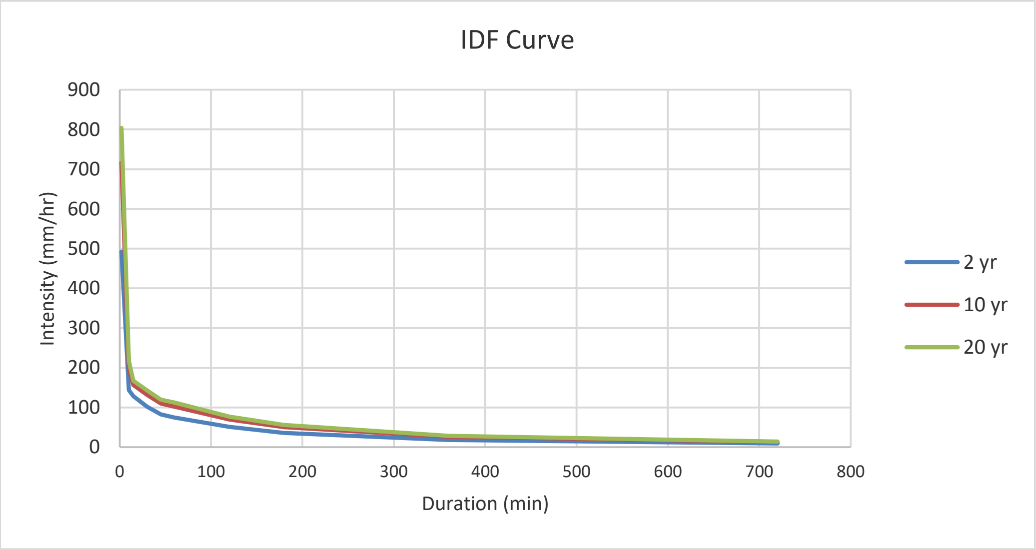


Figure 6-4 IDF Curves at Semarang station

After analysing the maximum rainfall values for each year at Ngasinan station from 1990 to 2015 in Table 6-2, it was found that the average rainfall from those maximum values is a bit higher than the 2-year rainfall return period from Gumbel analysis. Thus, the design storm for 2-year return period was made for disaggregating the daily rainfall for landslide event in Bompon and landslide event in Karangkobar (Figure 6-5). It was done in such a way until the rainfall depth (mm) reached the similar depth from the rainfall event on 21 December 2011 in Bompon and on 12 December 2014 in Karangkobar that triggered the landslide in those areas. In addition, the accumulated rainfall for both of the landslide events in Bompon and Karangkobar exceeds the 20-year return period from Gumbel analysis, and this was considered as the extreme event. Therefore, in this study, the extreme rainfall scenarios for defining the warning action used the 20-year return period.

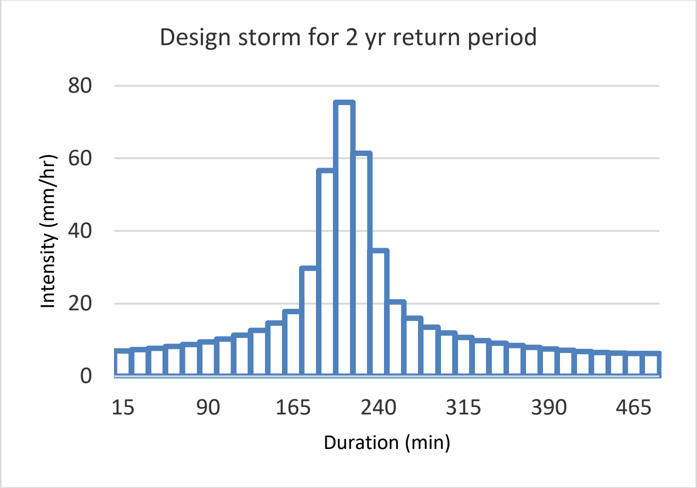


Figure 6-5 The alternating block for 2-year return period design storm

The available rainfall data that corresponded to the landslide occurrences on 21 December 2011 in Bompon was in daily with the rainfall 75 mm. Furthermore, the landslide in 2011 also influenced by the continuously 6-day rainfall prior to the landslide events in the area. The cumulative rainfall in this period was 150 mm and the total rainfall from 15 – 21 December 2011 amounted to about 225 mm. Although the accumulated rainfall for this period more than a return period of 1 in 20 years, the 75 mm of rainfall was still used for the simulation in Open Lisem. As because Open Lisem is an event-based model and it cannot calculate the antecedent rainfall, and to overcome this, for the modelling, the initial soil moisture should be considered high. As mentioned in section 4.3.2 the initial moisture for the simulation used 80% of the porosity, considering that especially during the rainy seasons, the high-intensity rainfalls result in increased soil moisture in the upper soil layers. To find out the intensity and duration of such the rainfall on 21 December 2011, then the 2-year design storm was used to disaggregate the daily rainfall to 15-minutes interval. The rainfall duration obtained from the 2-year return period design storm was 105 minutes or 1.75 hours. Finally, the 75 mm rainfall depth in 105 minutes was used in Open Lisem to simulate the landslide event on 21 December 2011 in Bompon.

As similar to Bompon, the available rainfall data in Karangkobar that corresponds to the landslide occurrences on 12 December 2014 was in daily with the rainfall 101.80 mm. In addition, the landslide also influenced by one day prior to the event, with the amount of rainfall 112.7 mm. The cumulative rainfall from 11 – 12 December 2014 was 214.5 mm. For the landslide simulation in Open Lisem, used the rainfall on the particular date when the landslide occurred with the same assumption as in Bompon's simulation. The resulting rainfall duration for the rainfall on 12 December 2014 after generating from the 2-year return period design storm was 240 minutes or 4 hours. Thus, the 101.80 mm rainfall depth in 240 minutes was used in open Lisem to simulate the landslide event in the area.

The resumes of the rainfall that were used for the simulation of the landslide events in Bompon on 21 December 2011 and in Karangkobar on 12 December 2014, and compared the results with the landslide inventory are shown in Table 6-3.

Table 6-3 The summary of rainfall for landslide events in both study areas

No	Location	Landslide event	Rainfall depth (mm)	Duration (minute)
1	Bompon	21 December 2011	75	105
2	Karangkobar	12 December 2014	101.8	240

To establish the rainfall scenarios, it should take into consideration of the rainfall analysis previously. For this study, three rainfall scenarios were proposed. It was done for the purpose to provide a different warning level for each settlement units that have been affected by the hazards as a consequence of simulating the different rainfall in Open Lisem. The rainfall scenario was set to have the significant different rainfall depth (in mm) by considering the maximum rainfall derived from the Gumbel analysis (see Figure 6-3). The determination of the rainfall scenario is applied for both of the study areas.

The first scenario utilized a rainfall threshold for giving the warning that has been established in Bompon area, which was 55 mm rainfall. The scenario 1 assumes that there is not any landslide occur in the area unless the threshold is exceeded. The second scenario corresponds to the 2-year return period rainfall derived from the equation from Gumbel analysis. This scenario assumes the rainfall depth increases significantly from scenario 1. The number of settlement units that are affected by the hydro-meteorological hazard will increase as well. The third scenario corresponds to the 20-year return period rainfall where it is considered as the worst scenario. The rainfall depth for this scenario is about 4 times from the scenario 1. For this scenario, almost all settlement units are affected by the hazard.

For all the three rainfall scenarios, the following assumptions were made:

1. The duration of the rainfall was kept the same in 6 hours. With the assumption that 6-hours rainfall is the effective rainfall duration with the highest rainfall intensity that may cause many problems, especially a landslide.
2. The initial soil moisture condition was assumed in the wet condition.
3. The simulation in Open Lisem used the initial stability option.

The assumption number 2 and 3 were explained in section 4.3.2. Table 6-4 summarizes the rainfall scenarios to define the warning level.

Table 6-4 Different rainfall scenarios to define the warning

Scenario 1		**Scenario 2**		**Scenario 3**	
Rainfall (mm)	Duration (hr)	Rainfall (mm)	Duration (hr)	Rainfall (mm)	Duration (hr)
55	6	132	6	206	6

6.1.3. Assessment of Soil Properties for Physical Modelling

There were two soil textures for both study areas (Figure 6-6). In Bompon, the soil textures were clay and silty clay loam. The clay is the dominant soil texture where it covered more than 70% of the area, and located from lower to upper slope, whereas the silty clay loam is mainly located in the plain area. On the other hand, in Karangkobar, the soil textures were clay and clay loam, with clay loam is the dominant soil texture in the area.

The soil samples in Bompon were analysed in the laboratory of Geography Faculty, University of Gadjah Mada. The analyzed soil parameters consist of Ksat and soil density inside the Bompon area, for which can be used for calculating the soil porosity (Table 6-5).

Table 6-5 Soil hydrology results for Bompon

No	X	Y	Ksat (mm/hr)	Bulk density (gr/cm3)	Porosity (%)	Soil texture
1	396964	9163936	202.85	1.60	38.29	SCL
2	397248	9163912	8.99	1.43	44.94	Cl

Table 6-5 above shows that Ksat values for Silty Clay Loam (SCL) are not in normal range and very high. If the results were compared to other Ksat values outside the study area, and they were also obtained from the laboratory analysis, the Ksat values range from 0.09 mm/hr to 24.93 mm/hr. For this, the Ksat value for clay still in that ranges, but it is still too high for clay. In addition, there was no information about the soil texture for each Ksat value outside the study area. Thus, these values were uncertain, in which Ksat for which soil texture. In the case of Bompon, the soil texture was obtained from the attribute in landform map. Since the soil texture in Bompon has been known, then it was decided to use the Ksat values from Saxton & Rawls (2006) by taking into consideration the land use type where the soil samples were taken, which are 25 mm/hr for Silty Clay Loam (SCL) and 2.5 mm/hr for Clay (Cl), in which such chosen values are within the Ksat value ranges from outside Bompon.

Additionally, based on the literature value (Swiss standard SN 670 010b and Minnesota Department of Transportation in http://www.geotechdata.info), the cohesion value for clay is 4 kPa, and for clay loam and silty clay loam ranges from 10 – 20 kPa. Internal friction angle for clay ranges from 27^0 – 35^0 and for clay loam and silty clay loam ranges from 18^0 – 32^0.

All the soil parameters, include the hydrology and geotechnical, which are used in the modelling for both study areas are summarized in Table 6-6 below.

Table 6-6 Soil parameters used for physical modelling in Open Lisem

Study areas	Soil types	Ksat (mm/hr)	Porosity (%)	Residual moisture (%)	Bulk density (gr/cm3)	Cohesion (kPa)	Internal Friction Angle (^{0})
Bompon	Clay	2.5 (i)	44.94 (ii)	27.6 (i)	1.43 (ii)	4 (iii)	35 (iii)
	Silty Clay Loam	25 (i)	38.29 (ii)	20.2 (i)	1.60 (ii)	20 (iv)	32 (iv)
Karangkobar	Clay	3.1 (i)	51 (i)	26.1 (i)	1.37 (i)	4 (iv)	35 (iv)
	Clay Loam	5.21 (i)	51 (i)	23.3 (i)	1.25 (i)	20 (iv)	32 (iv)

* (i) Saxton & Rawls (2006); (ii) Laboratory analysis; (iii) Swiss standard SN 670 010b, *Characteristic Coefficients of Soils*, Association of Swiss Road and Traffic Engineers (http://www.geotechdata.info); (iv) Minnesota Department of Transportation, *Pavement Design*, 2007 (http://www.geotechdata.info)

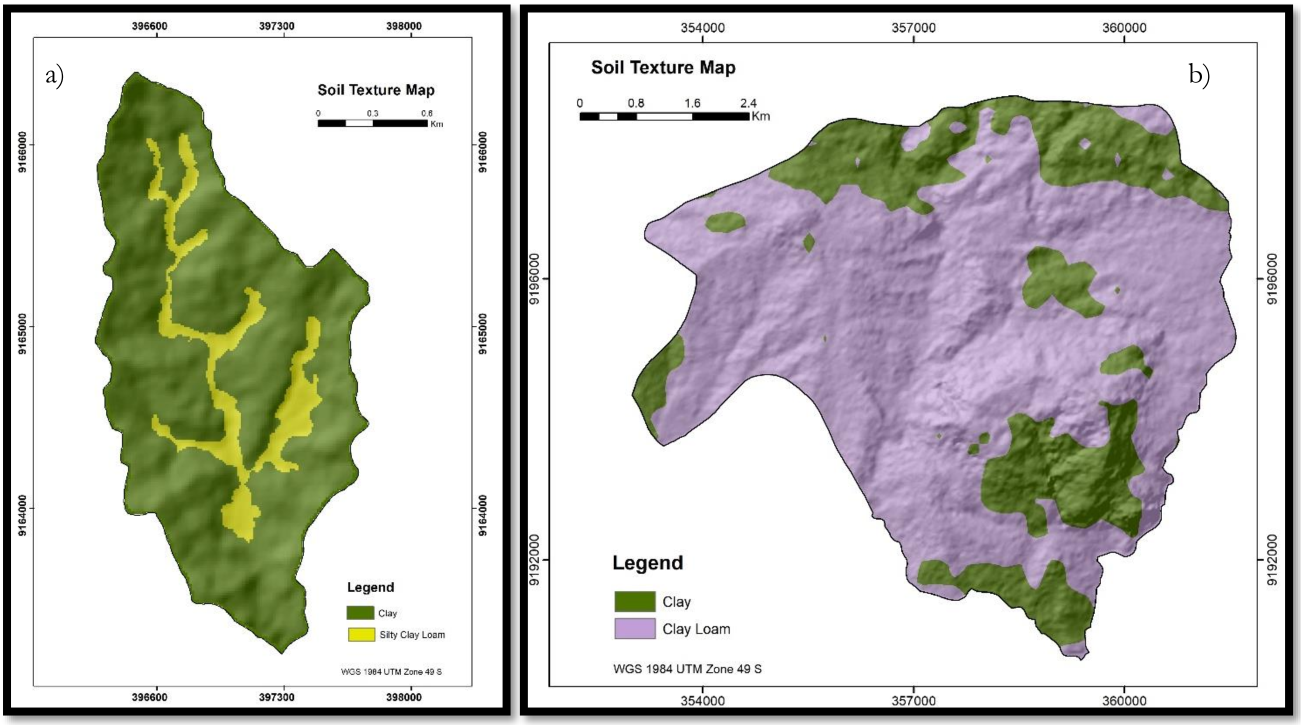
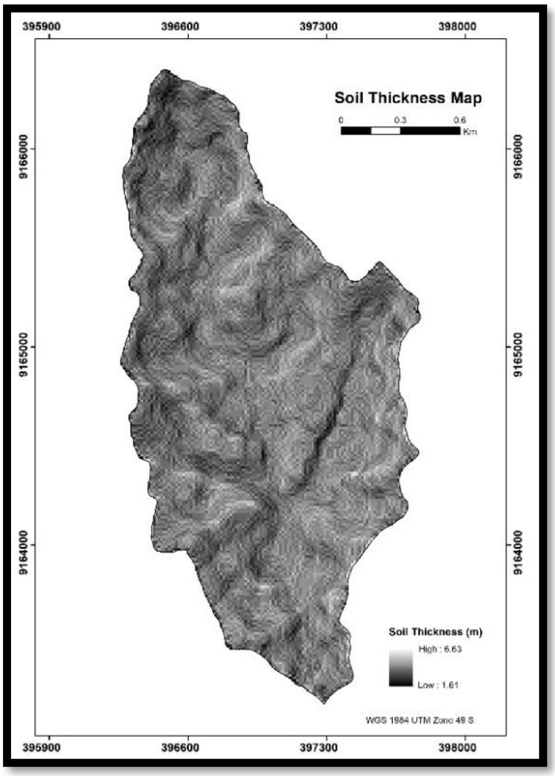
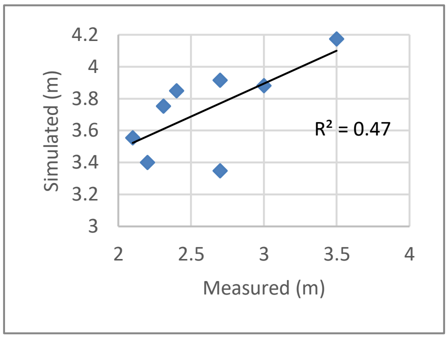


Figure 6-6 Soil texture map in Bompon (a) and in Karangkobar (b)

6.1.4. Soil Depth

The spatial distribution of soil thickness is shown in Figure 6-7 (left) where the soil is thicker at the lower elevation and closer to the channel and the soil is thinner at the steeper slope. The soil thickness varies from 1.61 m to 6.63 m. The fitted relationship between measured and simulated soil depth has a value R^2 of 47% with the average absolute error 1.12 m, and it is shown in Figure 6-7 (right). The fitted relationship is relatively low, the most probable reasons are the quality of Digital Elevation used in the modelling is not too detail and the low number of soil depth measurements in the field.





Measured (m)	Simulated (m)	Total Average error (m)
2.1	3.56	1.12
2.2	3.40	
2.31	3.75	
2.4	3.85	
2.7	3.91	
2.7	3.35	
3	3.88	
3.5	4.17	

Figure 6-7 The spatial distribution of simulated soil depth (left) and the fitted measurement and simulation (top right), the total average error (bottom right)

6.2. Discharge Calibration Results

Model calibration was done only for hydrology part and in Bompon area. As aforementioned, originally there were 3 discharge data in 2016, on 21 and 22 January 2016 and 10 February 2016, but only the latter was used because the amount of rainfall on this particular date was higher than the other discharge data.

The measured discharge has the runoff fraction 32.9% of the total amount of discharge 63,457 m^3. The delay time between the rainfall peak and the discharge peak is around 30 minutes. The duration of delay time is relatively short and give the high amount of discharge, and it means that the degree of erosion in this area is quite high. There is not enough time for water to infiltrate into the soil. Besides, the shape of this catchment is not too wide.

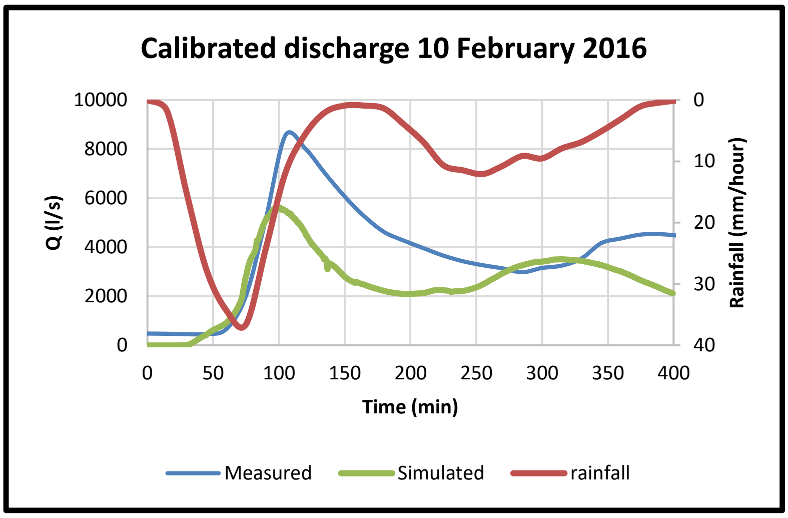


Figure 6-8 Calibration discharge result in Bompon.

The model showed underestimate result compared to the measured data (Figure 6-8). The under-estimation could be understood as the consequence of the lack of detail data, thus leading to the simplification of the input data. However, the calibration values in Open Lisem for the Ksat value 0.65, Manning (n) value 0.5, and Theta slope value 1.05, give the runoff fraction 32.6% which means 99% fitness between model and measured. Based on the high fitted value, then the model is considered as good for the next modelling of the safety factor and slope failure.

6.3. Physical Modelling Results In Bompon

This section shows all the results for landslide modelling in Bompon area. Subsection 6.3.1 describes the results for landslide modelling and compared the results with landslide inventory. Subsection 6.3.2 describes the results for landslide modelling based on different rainfall scenarios. The flood model result is not included in this section, as the flood does not either a frequent hazard or a big problem in the settlement area in Bompon.

6.3.1. Landslide Modelling

After all the input parameters have been prepared, then they were used to run in Open Lisem. The physical modelling was set up for the landslide events in 2011. In addition, all assumptions for the physical modelling were based on section 4.3.2, and the simulation used the rainfall from Table 6-3 for Bompon area.

The calibration values for the hydrology part as mentioned in the previous section were used for physical modelling. The models should be run separately for floods and landslides. There are 4 modelling outputs from the new Open Lisem, which are a safety factor map, a slope failure height map, a debris flow height map, and a flood depth map. For example, a flood depth map could be produced by flood modelling, and a safety factor map, a slope failure height map, and a debris flow height map are produced by landslide modelling. However, only 3 outputs from the physical modelling were used in the study, which are a safety factor map, a debris flow height map, and a flood depth map. Furthermore, the landslide events in 2011 were used to validate the safety factor results.

The result for completely dry condition showed that there are not any failures occurred in the area where the lowest safety factor value for this condition is 1.1 (Figure 6-9 a). On the other hand, the result for wet condition showed that only one location with the failures (Figure 6-9 b). The safety factor value on that location is 0.91.

The model result indicates that the soil initial moisture content as well as the rainfall are the influence factors to initiate the slope instability in the area. As can be seen from Table 6-7 that the critical area (SF 1 – 1.5) increases with the increase of initial moisture and likewise the stable area (SF > 1.5) decreases with the increase of initial moisture content.

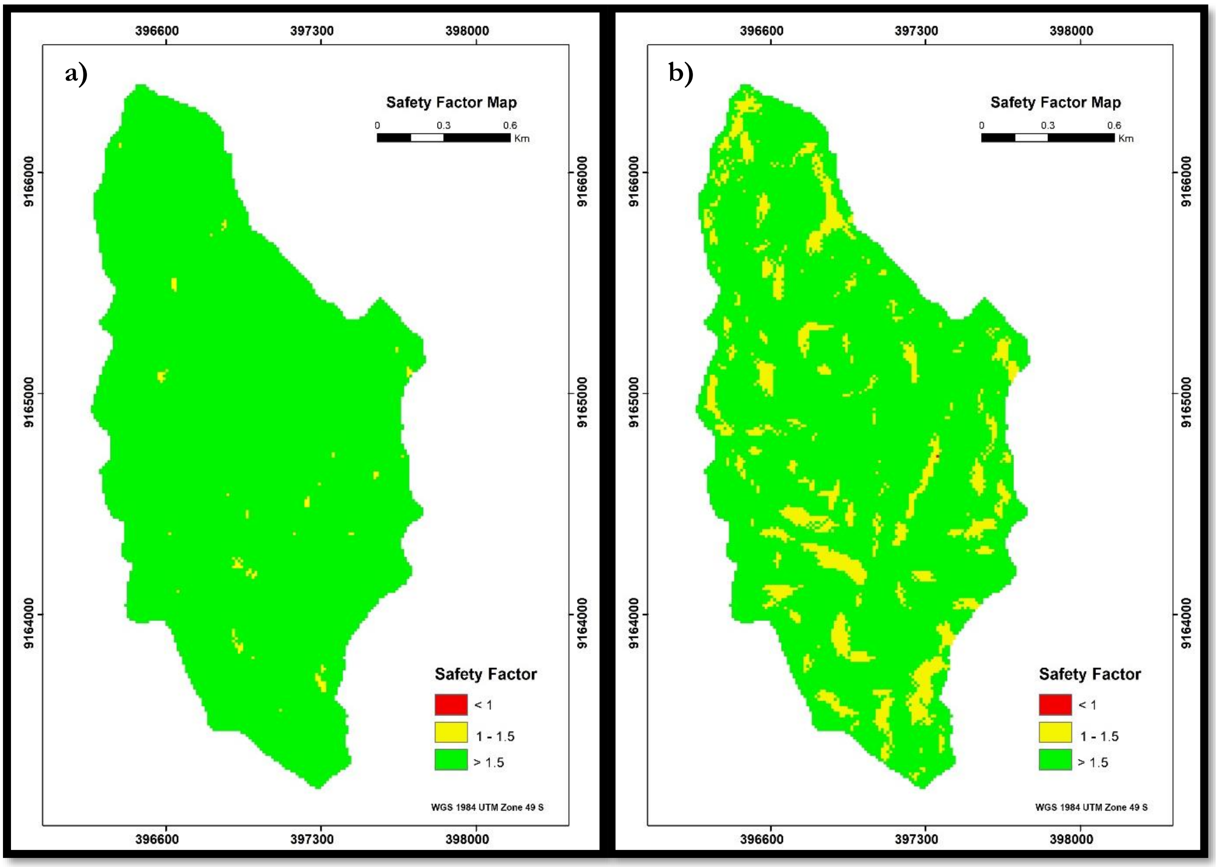


Figure 6-9 The result of safety factor for dry condition (a) and wet condition (b) in Bompon

Table 6-7 The coverage area based on the safety factor for both of soil condition in Bompon

Saturated Condition	Unit	Unstable (SF < 1)	Critical (SF 1 – 1.5)	Stable (SF > 1.5)	Total
Dry	Area (m²)	0	17,500	2,930,469	2,947,969
	Percentage (%)	0	0.59	99.41	100
Wet	Area (m²)	156	375,000	2,572,813	2,947,969
	Percentage (%)	0.01	12.72	87.27	100

If the simulation of safety factor result for wet condition is compared with the landslide events in 2011, it shows that all the landslides are located in stable area, with the lowest safety factor is 1.5 (Figure 6-10). The model could not predict the landslide events in 2011, as because the landslide types that occurred in 2011 are cut slopes. All locations are predicted stable (SF > 1.5). Since the size of the cut slopes are relatively small and the resolution of DEM used in this study was not too detail, thus they are hardly represented by using this DEM. Nevertheless, as shown in Figure 6-10, the blue box refers to the largest landslide in the area (see section 3.4.1), and the model is able to predict the landslide in the area, although it is categorized as critical (with SF 1 – 1.5).

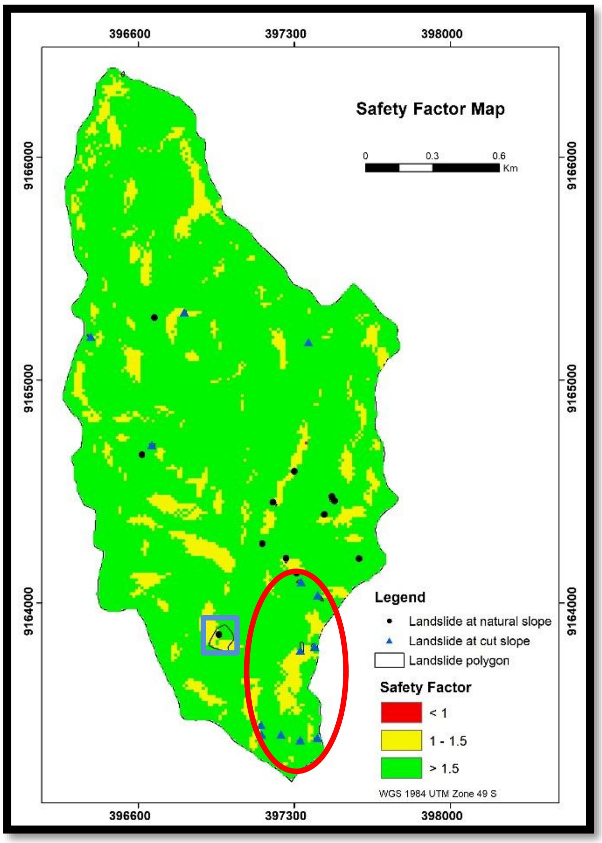


Figure 6-10 The safety factor map is compared to the landslide events in 2011. The red circle shows the landslide events in 2011. The blue box indicates the largest landslide dimension in the area

The result from land-use analysis shows that most of the landslides in 2011 occurred on the mixed plantation and settlement area. These data indicate that human activities play an important role on landslide occurrences. Cutting the slope for building their houses makes the area more unstable. Besides, the types of the plantation that they plant in the area are categorized as fast-growing trees, which in a few years can be harvested. The time between harvesting and planting can be considered as the critical time for the landslide occurrences.

Another output of landslide modelling in Open Lisem is a debris flow height map (Figure 6-11). The model indicates that the area still has the possibility to have a debris flow hazard. The maximum height of the debris flow from the simulation is 2.2 m. Although in reality, there has never been debris flow in the area. In Open Lisem, the simulation of a slope failure height leads to the calculation of a debris flow occurrence.

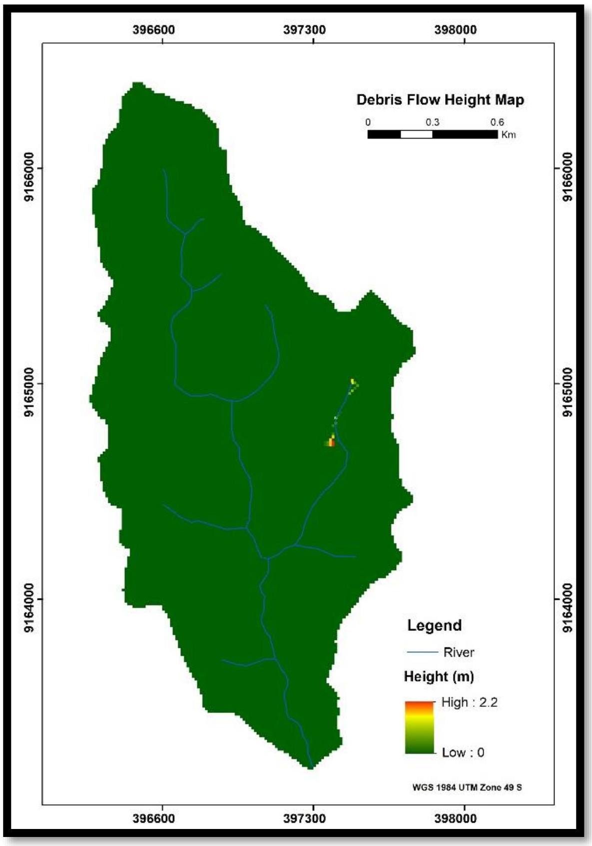


Figure 6-11 Debris flow height map result in Bompon

6.3.2. Landslide Modelling Based On Different Rainfall Scenarios

As aforementioned, the flood modelling was omitted for Bompon area. The assumptions for these simulations were similar to the previous simulation, as mentioned in section 4.3.2. However, the rainfall depth and the duration for this modelling was different. The modelling used the rainfall from Table 6-4.

The simulation results of the safety factor for all rainfall scenarios are displayed in Figure 6-12. There are not any significant differences between each scenario. Figure 6-12 (a) shows only one location which considers as unstable with the SF < 1 (in the figures, unstable areas are marked with the red circle). In addition, Figure 6-12 (b) shows two locations as unstable (SF < 1), and Figure 6-12 (c) shows three locations as unstable (SF < 1).

Table 6-8 shows the summary of the area which considers as unstable, critical, and stable, for all rainfall scenarios. The increasing of the unstable area for each scenario is only 0.01%, whereas the stable area remains steady. From the results, it is found that the magnitude of the rainfall does not give the great effect to the slope failure (SF < 1), but in fact, the occurrence of rainfall gives more impact to the slope failure.

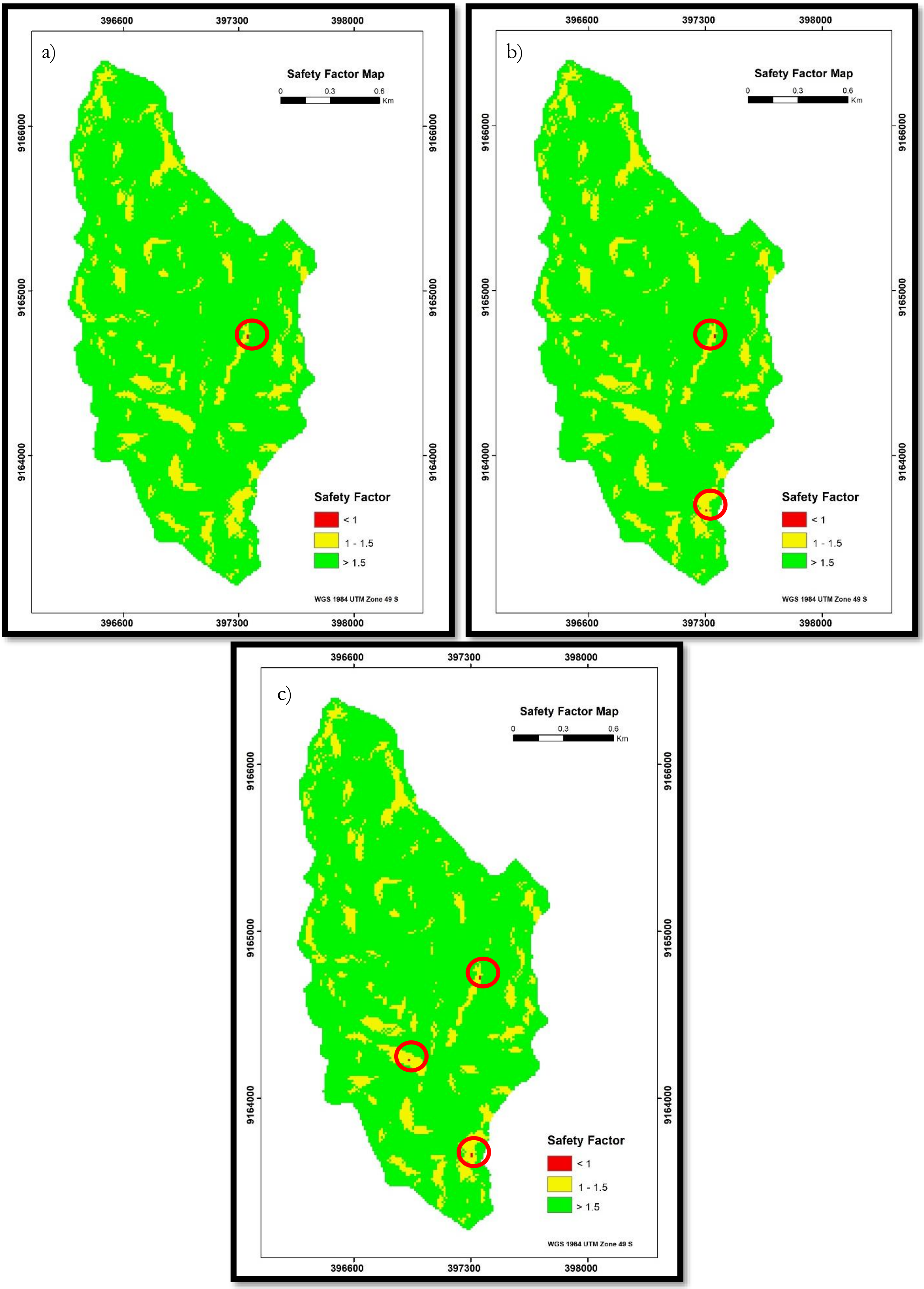


Figure 6-12 The simulation results for the safety factor which correspond to the rainfall scenario in Bompon. (a) is scenario 1, (b) is scenario 2, and (c) is scenario 3

Table 6-8 The statistics of the safety factor results for all scenarios in Bompon

Scenario	Unit	Unstable (SF < 1)	Critical (SF 1 – 1.5)	Stable (SF > 1.5)
1	Area (m^2)	312.5	374,844	2,572,813
	Percentage (%)	0.01	12.72	87.27
2	Area (m^2)	468.75	374,688	2,572,813
	Percentage (%)	0.02	12.71	87.27
3	Area (m^2)	781.25	374,375	2,572,813
	Percentage (%)	0.03	12.70	87.27

The simulation of the debris flow height for all rainfall scenarios are displayed in Figure 6-13. Unlike the safety factor result, the simulation of debris flow height in the area shows the increasing of the affected area as a consequent of the implementation of the rainfall scenarios. However, it is not only the area increases but also the height increases. Figure 6-13 (a) is scenario 1 which shows the debris flow height only occurs in the eastern part with the maximum height is 1.8 m. Figure 6-13 (b) is scenario 2. The figure shows several locations which are affected by the debris flow, and the maximum debris flow height is 2.6 m. Figure 6-13 (c) is scenario 3. The area extends to the northern part, and the maximum debris flow height is 3.7 m.

Table 6-9 below shows the summaries of the areas that are affected by the debris flow height for all rainfall scenarios with hazard classes as low, moderate, and high. Scenario 3 is the worst scenario and results in almost 100% the increasing debris flow height from scenario 1 to scenario 3.

Table 6-9 The statistics of the debris flow height results for all scenarios in Bompon

Scenario	Unit	Low (< 0.5 m)	Moderate (0.5 m – 1 m)	High (> 1 m)
1	Area (m^2)	2,946,563	781	625
	Percentage (%)	99.95	0.03	0.02
2	Area (m^2)	2,935,781	4,375	7,813
	Percentage (%)	99.59	0.15	0.27
3	Area (m^2)	2,922,344	5,625	20,000
	Percentage (%)	99.13	0.19	0.68

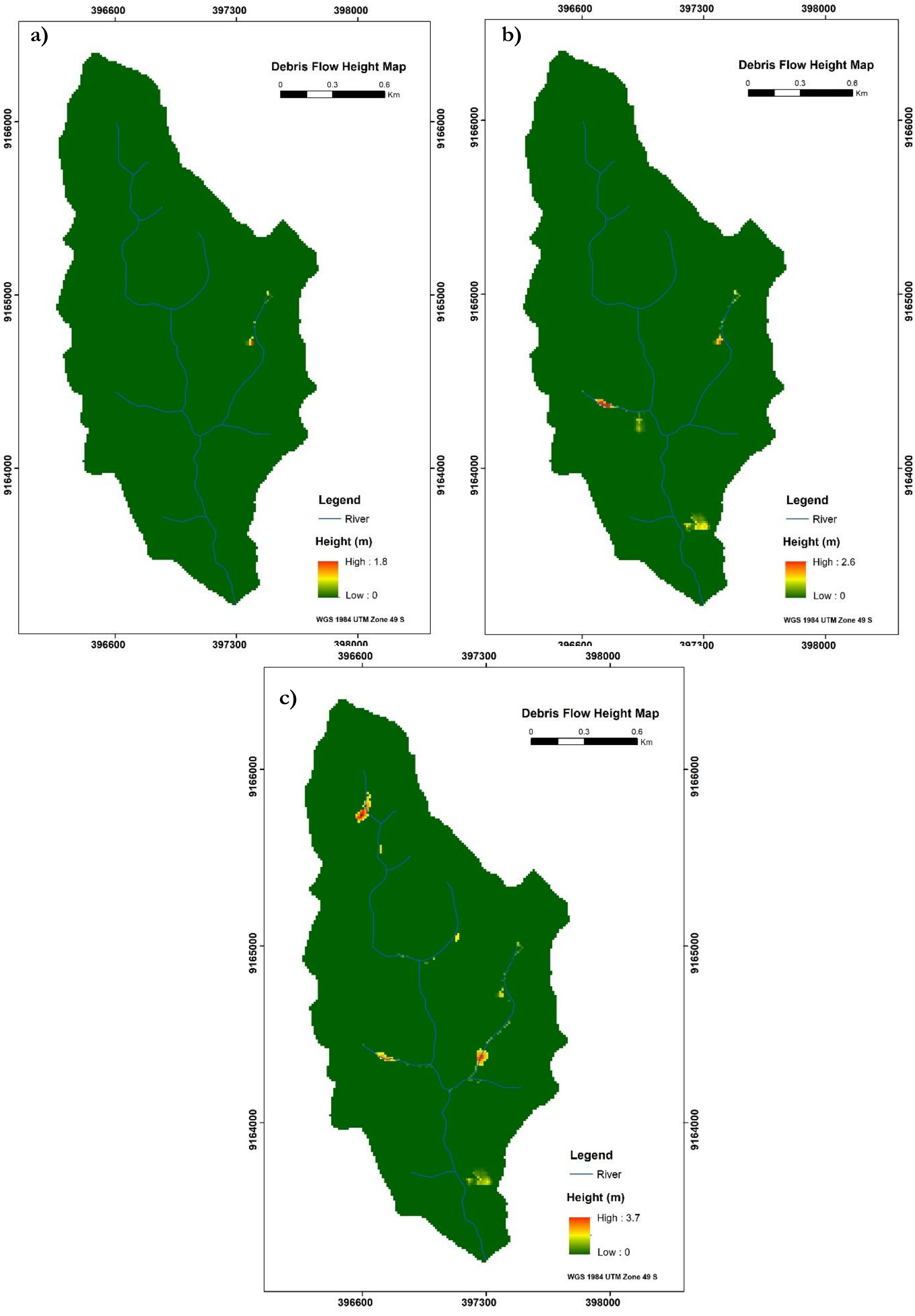


Figure 6-13 The simulation results for the debris flow height which correspond to the rainfall scenario in Bompon. (a) is scenario 1, (b) is scenario 2, and (c) is scenario 3

6.4. Physical Modelling Results In Karangkobar

The physical modelling in this area includes the flood modelling, as the fieldwork did not carry out in the area. Thus, it was assumed that all hydro-meteorological hazards from the simulation in Open Lisem exist in Karangkobar. Subsection 6.4.1 described the results for landslide and flood modelling and compared the landslide model results with landslide inventory. Subsection 6.4.2 describes the results for landslide and flood modelling based on different rainfall scenarios.

6.4.1. Landslide and Flood Modelling

As similar to the landslide modelling in Bompon, this area also used the discharge calibration result as an input for hydrology part in Open Lisem. The modelling was set for the landslide events in December 2014. Furthermore, all assumptions for the physical modelling were based on section 4.3.2, and the simulation used the rainfall from Table 6-3 for Karangkobar area.

Using the original soil depth obtained from the literature (Hengl et al., 2017), the result of safety factor in Open Lisem for the completely dry condition shows that the area has many unstable areas with the lowest safety factor 0.35. The lowest safety factor is located on the slope 62^0. Theoretically, in such condition, no failures occurred or no areas having the safety factor < 1. However, using the new Open Lisem, the unexpected result was appeared. A possible reason for the low value of the safety factor in completely dry condition is the uncertainty related to the soil depth map. To calibrate the model, the critical soil depth map was calculated in Arc Map and considered the safety factor 1.1, using equation 3 as described in section 4.4.4. Still, inconsistencies were observed between the result of critical soil depth in the area compared to the original soil depth from the literature. The result from the calculation of critical soil depth varied from – 5 m to 83 m, even it is worse than the original soil depth. Therefore, it was decided to use the original soil depth for landslide modelling in this area.

The slope stability simulation for the whole area with the wet condition results in the lowest safety factor value 0.24. The difference of the lowest safety factor value in the same location between completely dry and wet condition can be calculated as $\Delta SF = (0.35\text{-}0.24)/0.35 = 31.4\%$. It is clear from the result that the failure in this area is mostly influenced by the soil initial moisture condition as well as the rainfall event. Table 6-10 shows the percentage area of the safety factor results for both soil saturated condition.

Table 6-10 The safety factor area for both of soil condition in Karangkobar

Saturated Condition	Unit	Unstable (SF < 1)	Critical (SF 1 – 1.5)	Stable (SF > 1.5)	Total
Dry	Area (m^2)	505,313	2,448,594	39,212,656	42,166,563
	Percentage (%)	1.2	5.8	93	100
Wet	Area (m^2)	3,519,844	8,277,500	30,369,219	42,166,563
	Percentage (%)	8.3	19.6	72	100

The landslide modelling was validated by using the landslide events in 2014 (Figure 6-14). The result for completely dry condition shows that no landslides are located in unstable areas (SF < 1), and the lowest safety factor is 1.3. On the other hand, for the wet condition shows that there are 3 locations are predicted unstable (SF < 1), 4 locations at the critical area (SF 1 – 1.5), and the remaining (3 locations) as stable (SF > 1.5). Although the model could predict the landslide locations, the result still over-predicted. As shown in Figure 6-14 b, there are many unstable areas (SF < 1) produced from the simulation.

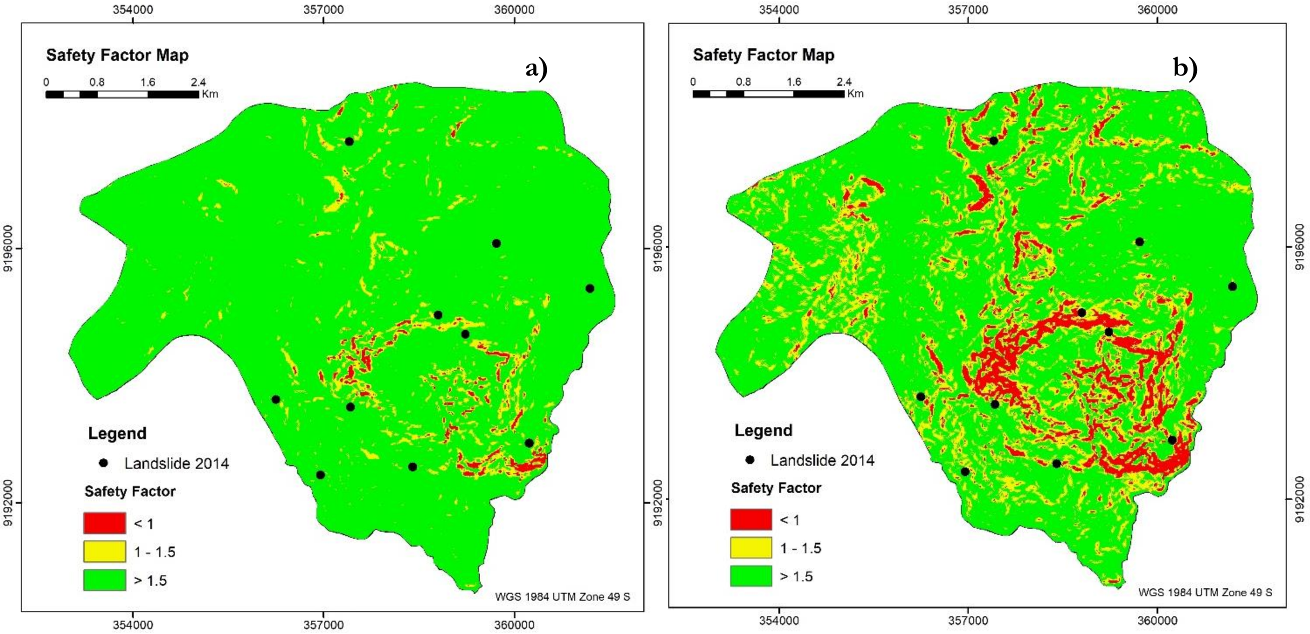


Figure 6-14 The result of safety factor for completely dry (a) and wet condition (b) in Karangkobar

The other outputs of Open Lisem in Karangkobar area are a flood depth map and a debris flow height map (Figure 6-15). The flood map showed the probability in the area to have the flood hazard with the maximum flood depth is 6.9 m. Also, the debris flow model indicates that the area has a high probability of the occurrence of debris flow hazard. There are 7 out of 16 run out polygon are predicted in the debris flow height map. Nevertheless, the debris flow model shows an over-prediction result with numerous locations predicted as debris flow with the maximum debris flow height is 18 m.

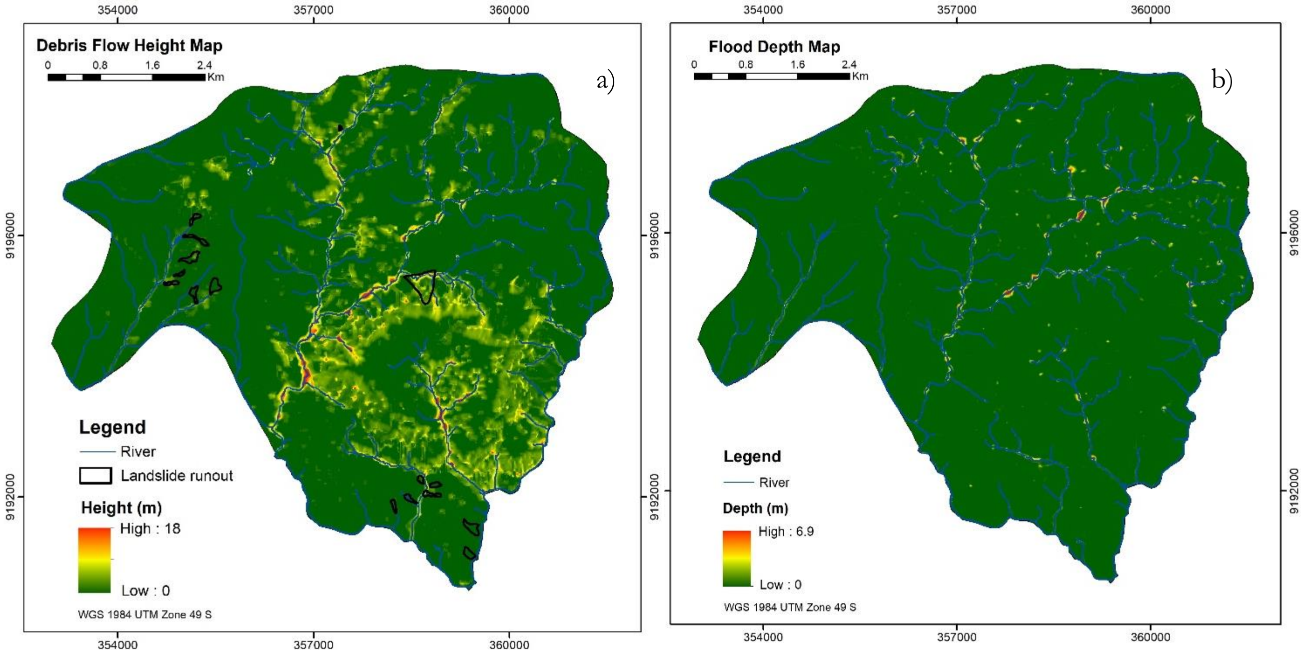


Figure 6-15 Debris flow height map (a) and Flood depth map (b) in Karangkobar

6.4.2. Landslide and Flood Modelling Based On Different Rainfall Scenarios

For Karangkobar, all the physical modelling results, which consist of safety factor map, debris flow height map, and flood depth map, were simulated by using the different rainfall scenarios. The assumptions for these simulations were based on section 4.3.2, and the rainfall depth and the duration for this simulation were based on Table 6-4.

The simulation results of the safety factor for all rainfall scenarios are displayed in Figure 6-16. The safety factor result for this simulation shows no differences for each scenario. The spatial distribution of safety factor from this simulation is similar to the previous result in section 6.4.1. The area which considers unstable actually higher compared to Bompon's safety factor results. It is evident that the slope failure in the simulation of Open Lisem only influenced by the presence of the rainfall, not by the increasing of the amount of rainfall. Table 6-11 shows the summary of the area which considers as unstable, critical, and stable, for all rainfall scenarios.

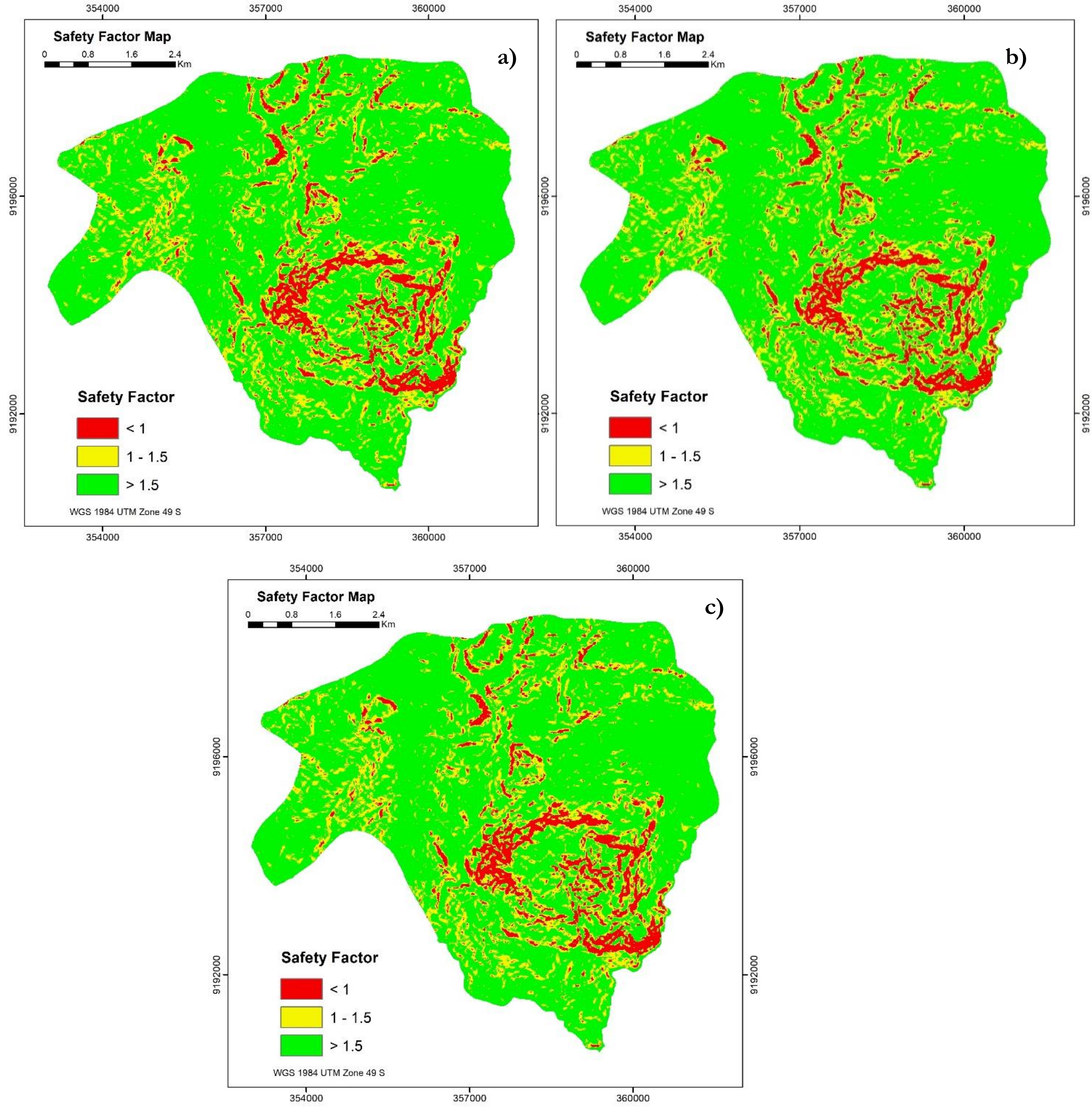


Figure 6-16 The simulation results for the safety factor which correspond to the rainfall scenario in Karangkobar (a) is scenario 1, (b) is scenario 2, and (c) is scenario 3

Table 6-11 The statistics of the safety factor results for all scenarios in Karangkobar

Scenario	Unit	Unstable (SF < 1)	Critical (SF 1 – 1.5)	Stable (SF > 1.5)
1	Area (m^2)	3,520,313	8,076,563	28,773,438
	Percentage (%)	8.72	20.01	71.27
2	Area (m^2)	3,520,313	8,076,563	28,773,438
	Percentage (%)	8.72	20.01	71.27
3	Area (m^2)	3,520,313	8,076,563	28,773,438
	Percentage (%)	8.72	20.01	71.27

The simulation of the debris flow height for all rainfall scenarios are displayed in Figure 6-17. The debris flow height gives the increasing of the affected area for each scenario. However, the increasing of the debris flow height only 5% for the class "high" (depth > 1 m) from scenario 1 to scenario 3. The differences, in term of the extent area and the height, between scenario 1, scenario 2, and scenario 3 are not as high as Bompon's debris flow height result. In addition, the maximum height of the debris flow decreases from scenario 1 to scenario 3, as shown in Figure 6-17 a and c. The lower percentage as well as the decrease of the height between scenario 1 and scenario 3 are probably influenced by the soil depth used in the simulation. The soil depth in this simulation is not as thick as in Bompon. Figure 6-17 (a), (b), and (c), with the red circle shows in that particular location is the most significant difference from scenario 1 to scenario 3. The area of debris flow height in scenario 1 expands when scenario 2 and 3 are applied. Actually, there are the differences for the other debris flow height areas in each scenario, but they are hardly to be seen.

Table 6-12 shows the summaries of the areas which are affected by debris flow height for all rainfall scenarios with hazard classes as low, moderate, and high. From the table below, the differences between scenario 1, scenario 2, and scenario 3 are perceivable clearly.

Table 6-12 The statistics of the debris flow height results for all scenarios in Karangkobar

Scenario	Unit	Low (< 0.5 m)	Moderate (0.5 m – 1 m)	High (> 1 m)
1	Area (m^2)	32,307,500	3,052,344	6,806,719
	Percentage (%)	76.62	7.24	16.14
2	Area (m^2)	32,166,719	3,057,031	6,942,813
	Percentage (%)	76.28	7.25	16.47
3	Area (m^2)	31,935,781	3,067,500	7,163,281
	Percentage (%)	75.74	7.27	16.99

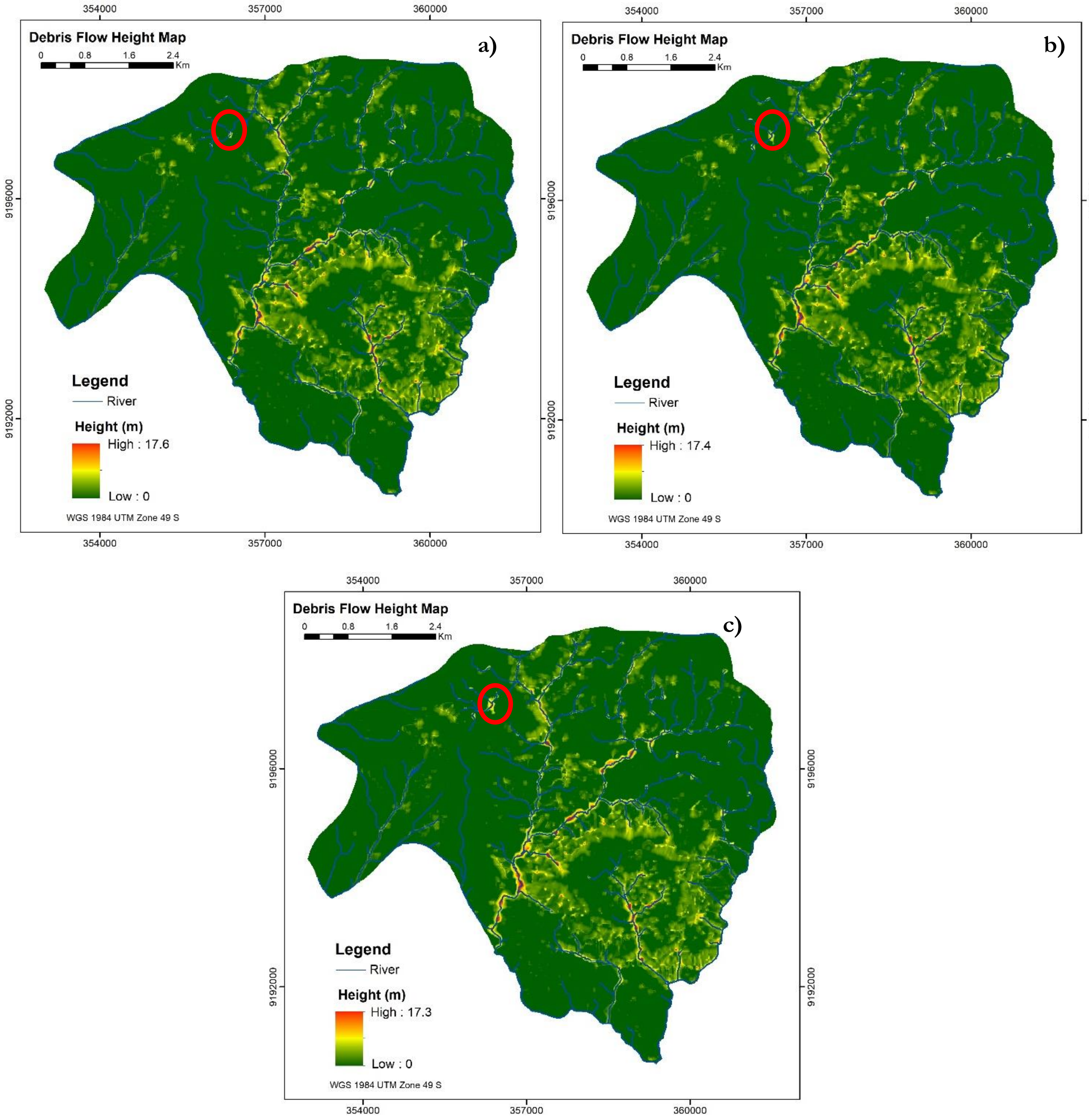


Figure 6-17 The simulation results for the debris flow height which correspond to the rainfall scenario in Karangkobar. (a) is scenario 1, (b) is scenario 2, and (c) is scenario 3. Red circle shows the most significant differences for each scenario

The simulation of the flood depth for all rainfall scenarios are displayed in Figure 6-18. The flood depth gives the significant differences for each scenario, particularly for scenario 1 and scenario 3. It is only flood depth has a notable correlation with the increasing of rainfall. As shown in Figure 6-18, which illustrates with the red circles, the extent flood area increases with the increasing magnitude of rainfall. Furthermore, the increasing is not only the area but also the flood depth. Figure 6-18 (a) scenario 1 shows that the maximum flood depth is 6.6 m, and in scenario 2, it rises to 8.1 m, as shown in Figure 6-18 (b), and finally in Figure 6-18 (c) as the worst scenario, the maximum flood depth is 8.4 m, and also the extent flood area is wider than the scenario 1 and scenario 2.

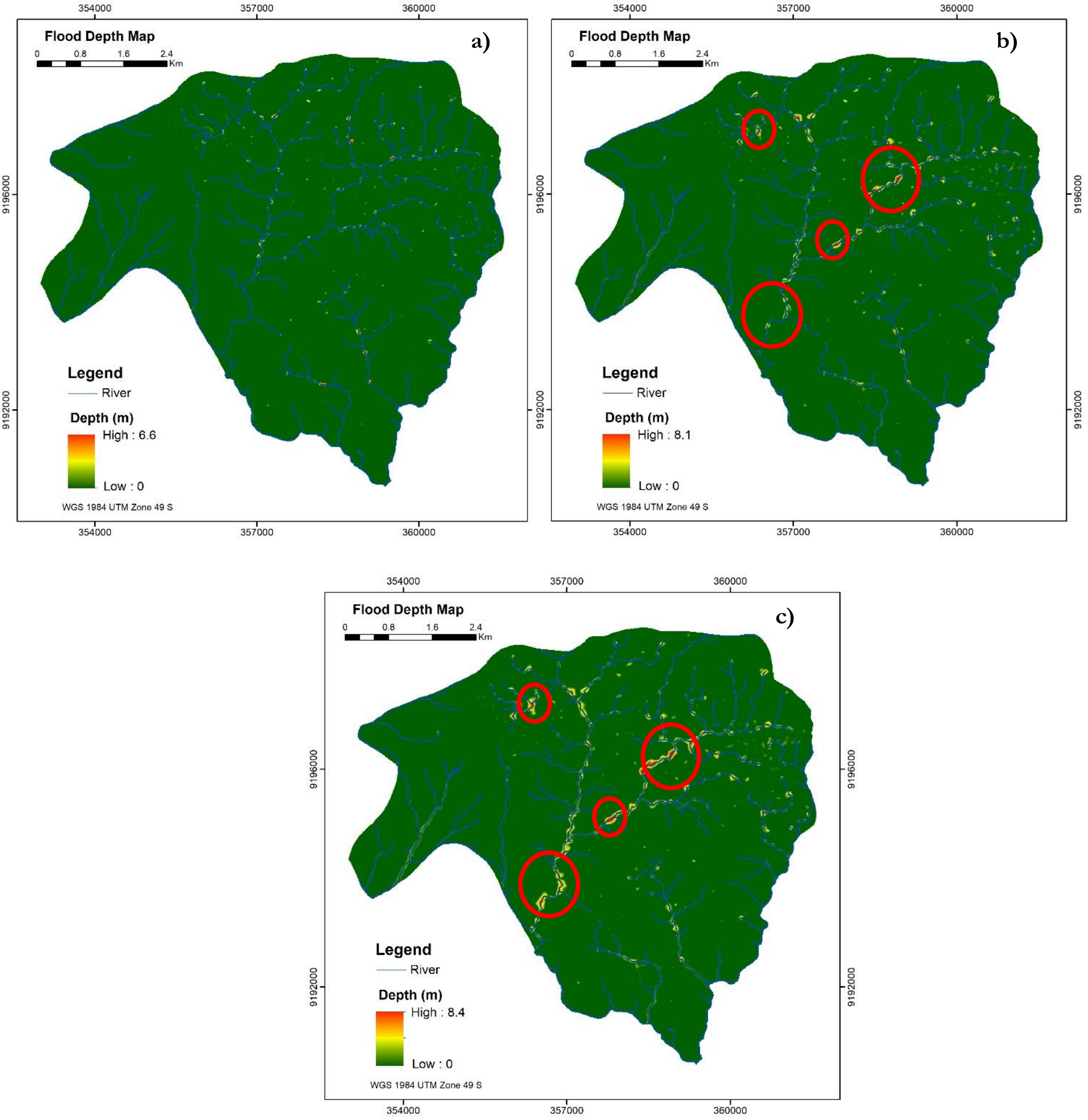


Figure 6-18 The simulation results for the flood depth which correspond to the rainfall scenario in Karangkobar. (a) is scenario 1, (b) is scenario 2, and (c) is scenario 3. Red circles indicate the significant differences

Table 6-13 below shows the summaries of the areas which are affected by the flood depth for all rainfall scenarios with hazard classes as low, moderate, and high. From the table below, the differences between each scenario can be seen clearly.

Table 6-13 The statistics of the flood depth results for all scenarios in Karangkobar

Scenario	Unit	Low (< 0.5 m)	Moderate (0.5 m – 1 m)	High (> 1 m)
1	Area (m^2)	41,781,875	186,250	198,438
	Percentage (%)	99.09	0.44	0.47
2	Area (m^2)	40,795,313	585,000	786,250
	Percentage (%)	96.75	1.39	1.86
3	Area (m^2)	37,451,094	986,094	3,389,844
	Percentage (%)	89.54	2.36	8.10

7. APPLICATION OF THE EARLY WARNING SYSTEM FOR DIFFERENT RAINFALL SCENARIOS

7.1. Local Implementation of Landslide Early Warning System

After the simulation of landslide mitigation in Bompon area that was held by BPBD in 2015, particularly in Margoyoso village, the local inhabitants know the landslide mitigation procedure if the landslide occurred in their area. Additionally, the local authority has formed the responsive unit work or it is called Fortis (in Bahasa), with the main responsibilities are to inform the local people about the landslide surrounding their area and to monitor continuously the area which is prone to landslide. Moreover, the responsive unit work (Fortis) also being equipped with the emergency response tools.

The implementation of Landslide Early Warning System in the Bompon area is based on the actual evidence, such as a heavy rainfall or a report from an eyewitness. Based on the short interview with the head of Hamlet (Kadus) of Kalisari, he said that the LEWS is performed if there is a heavy rainfall in several hours. When rainfall thresholds are exceeded, then he sends the message or makes a phone call to the head of neighbourhood groups (RT) and to the members of Fortis, to inspect their area. He also inspects the surrounding area. If there is a report that a soil movement occurred in an area, they must go to that location and check whether the movements are dangerous or not. If it is not too dangerous, the alert does not be issued. Nevertheless, as the head of Hamlet, he has an obligation to give the information to his resident to be always aware and pay more attention if there is a heavy rainfall, especially if the rain occurs during the night. To do such activities require a good communication and cooperation between the local authorities and the inhabitants. The local monitoring system in Bompon is displayed in Figure 7-1.

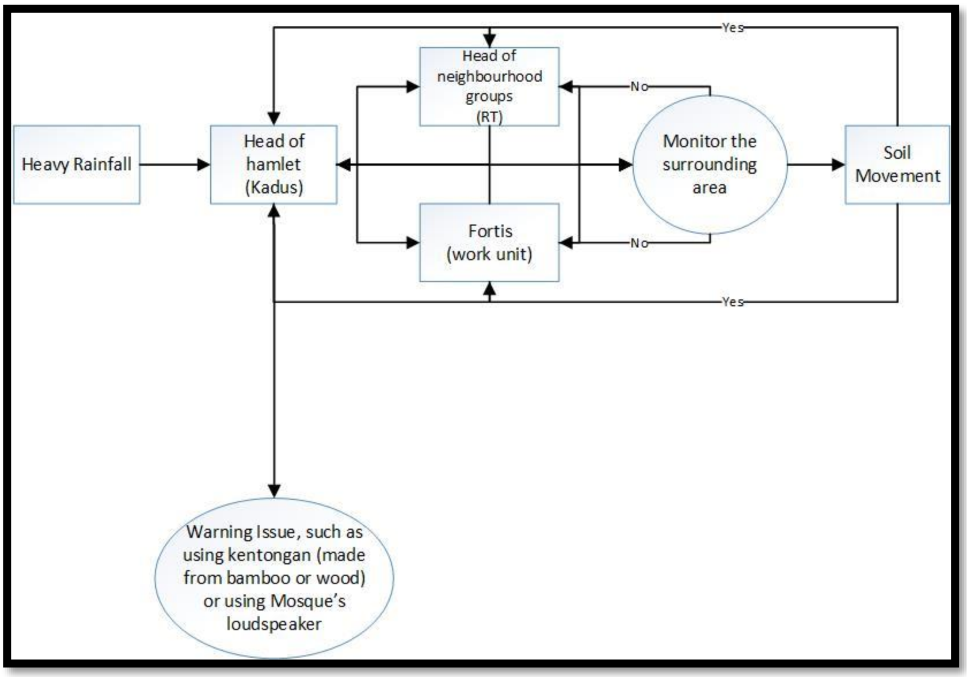


Figure 7-1 Local implementation of EWS in Bompon

In this study, the results of physical modelling and the utilization of different rainfall scenarios are used to enhance the local implementation of landslide early warning system in Bompon in order to give a different warning at a particular area with a given amount of rainfall. This is done for both study areas.

7.2. Application of the Landslide Early Warning System in Bompon

Once the simulation of the different rainfall scenario has been done, the results, which are safety factor maps and debris flow height maps, are integrated into the settlement units. For this study, the level of the hydro-meteorological hazards to issue the warning is the highest hazard level, which means for the safety factor is "unstable" (SF < 1) and for the debris flow height is "high" (height > 1 m).

The integration of the unstable area (SF < 1) and the settlement units shows that no settlement units are located within unstable area for all rainfall scenarios. In addition, the spatial distributions of the settlement units that are located in the unstable, critical, and stable areas for each scenario are the same (Figure 7-2). On the other hand, the integration of debris flow height and the settlement units shows no settlement units which are affected by the debris flow height in scenario 1. However, there is one settlement unit which is affected in scenario 2 and scenario 3, and no differences result between scenario 2 and scenario 3 (Figure 7-3). The summaries of settlement units which are affected by the hydro-meteorological hazards in Bompon are shown in Table 7-1.

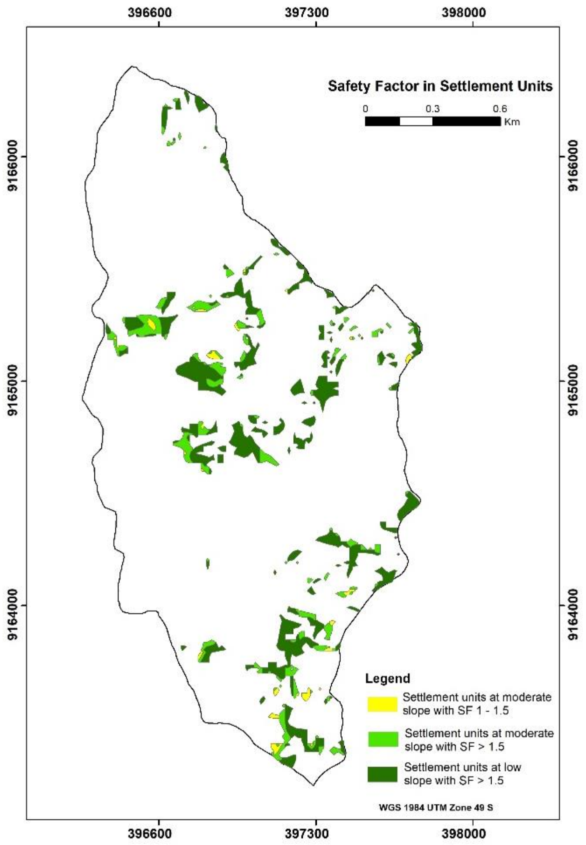


Figure 7-2 The safety factor distribution for each settlement units in Bompon.

Table 7-1 The affected settlement units after modelling with different rainfall scenarios in Bompon

No	Hazard type		Rainfall Scenarios		
			I	II	III
1	Landslide (SF < 1)	Number of units affected	0	0	0
		Area affected (m^2)	0	0	0
		Percentage affected (%)	0	0	0
2	Debris flow (Height > 1 m)	Number of units affected	0	1	1
		Area affected (m^2)	0	156	156
		Percentage affected (%)	0	0.06	0.06

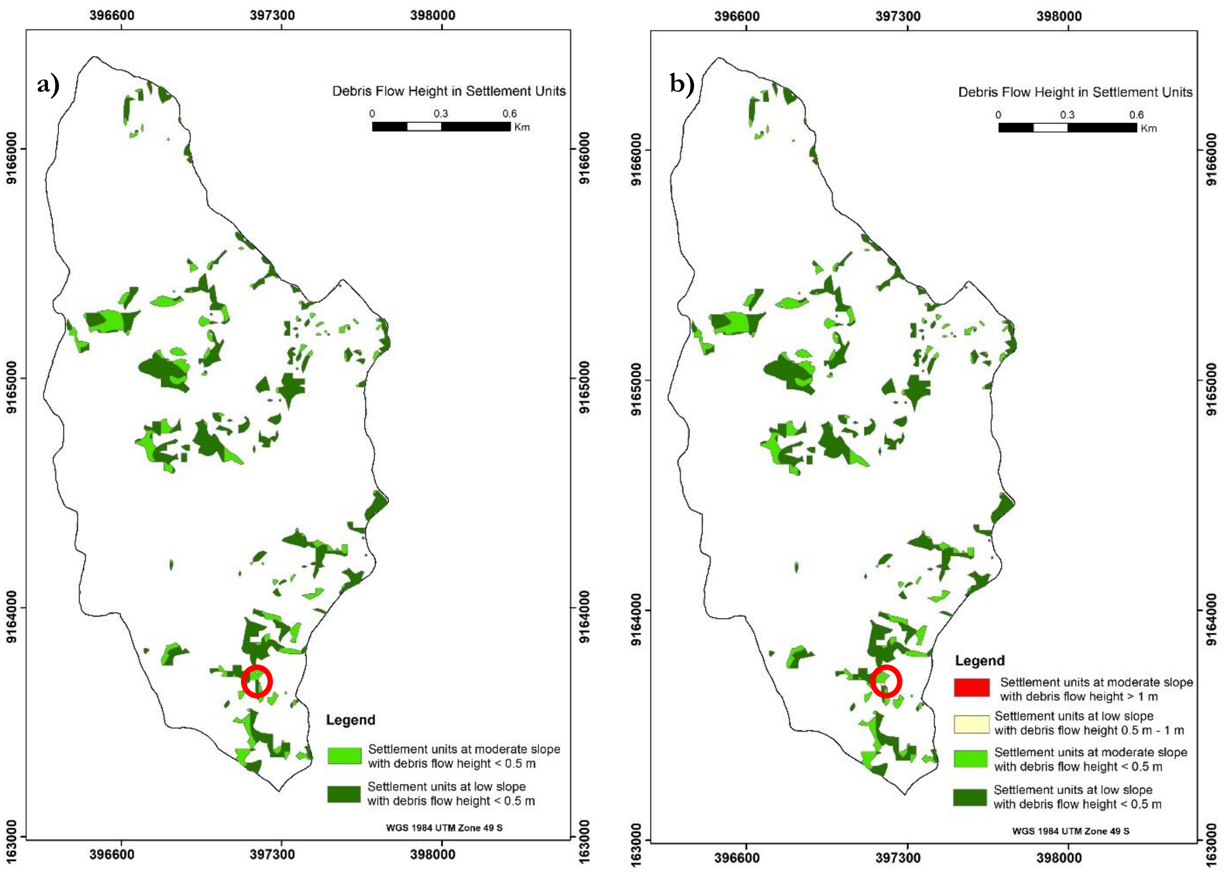


Figure 7-3 The debris flow height maps for each settlement units in Bompon. (a) is scenario 1, (b) is scenario 2 and scenario 3. Red circle shows the different for each scenario.

From the results above, the hazard matrix for Bompon area can be made. Since, only one settlement unit is affected by the high debris flow hazard (height > 1 m), with the unit ID "moderate * 57, and there are no settlement units which are located in unstable area (SF < 1) for all rainfall scenarios, then the hazard matrix only provides one settlement unit with the highest level of hydro-meteorological hazard (Table 7-2). Therefore, this particular settlement unit can be given the warning if the rainfall in scenario 2 is reached. Considering there is not any difference between scenario 2 and scenario 3, which means if the settlement unit is affected by the hazard from scenario 2, but the effect is similar to the hazard from scenario 3, thus the warning level must be applied to the highest warning. As mentioned in section 4.6., the action that should be taken for this warning level is the evacuation of the people in that particular settlement unit.

Table 7-2 Hazard matrix in each settlement unit for each scenario in Bompon. The sign "x" means a hazard exists in the settlement unit while "-" means no hazard in the settlement unit

Scenario 1			
Unit ID	Landslide	Debris flow	Flood
Moderate * 57	-	-	-

Scenario 2			
Unit ID	Landslide	Debris flow	Flood
Moderate * 57	-	x	-

Scenario 3			
Unit ID	Landslide	Debris flow	Flood
Moderate * 57	-	x	-

7.3. Application of the Landslide Early Warning System in Karangkobar

As similar what has been done in Bompon area, the same simulation also applies for this area. However, the flood modelling is included in the simulation. The same hazard level also used to allow the warning issue, which used the highest hazard level, which are the safety factor is "unstable" (SF < 1), the debris flow height is "high" (height > 1 m), and the flood depth is "high" (depth > 1 m).

The integration of the unstable area (SF < 1) and the settlement units shows that there are 26 settlement units are located within unstable area, with 18 settlement units at moderate slope and 8 settlement units at steep slope. There are no differences for all scenarios for this simulation (Figure 7-4). The number of the settlement units which are located in the unstable area are the same for each scenario.

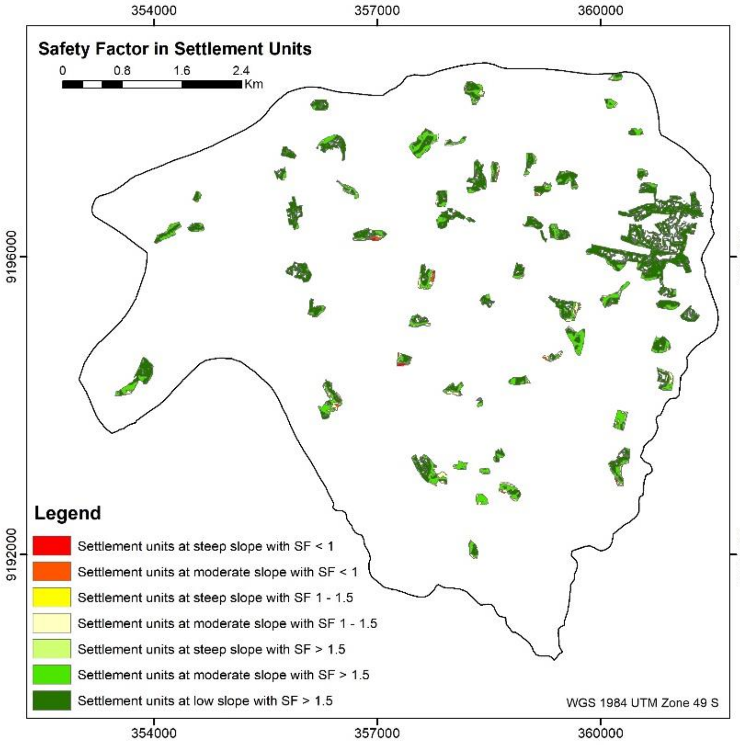


Figure 7-4 The safety factor distribution for each settlement units for all rainfall scenarios in Karangkobar (no differences for each scenario)

The integration results of the debris flow height and the settlement units for each scenario can be described as follows: 1) In scenario 1, there are 46 settlement units which are affected by high debris flow hazard with the height > 1 m, and the units are separated by 3 slope classes, which are 17 settlement units at low slope, 22 settlement units at moderate slope, and 7 settlement units at steep slope. 2) The number of settlement units in scenario 2 which are affected by debris flow height is similar to scenario 1, but there is a little difference in the area. 3) In scenario 3, there are 48 settlement units which are affected by the debris flow height. There are two additional settlement units which are affected by debris flow height at low slope, with a total 19 settlement units, and the remaining settlement units at moderate and steep slope are the same with other scenarios. However, the differences between scenario 1 and scenario 3 are not very significant. If the affected areas in scenario 1 are compared to the affected areas in scenario 3, the differences only 5.6 %. Given a high amount of rainfall in scenario 3, the differences are still not very high. The debris flow height results are shown in Figure 7-5.

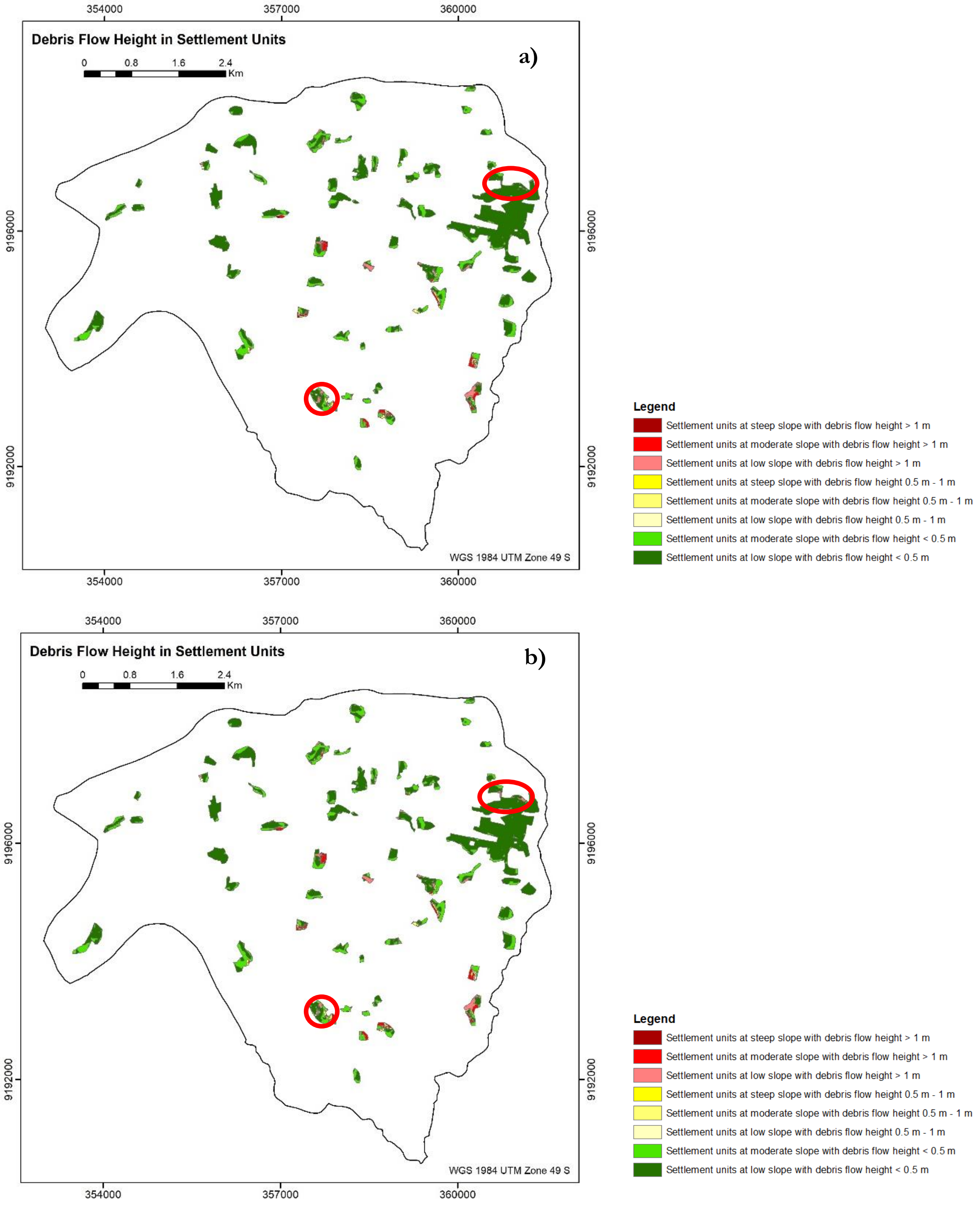


Figure 7-5 The debris flow height maps for each settlement units in Karangkobar. (a) is scenario 1 and scenario 2, (b) is scenario 3. Red circles show the differences for each scenario.

On the other hand, the integration of flood depth and the settlement units shows the significant differences. In scenario 1, there are 4 settlement units which are affected by the flood, and they all are located at low slope. In scenario 2, there are 10 settlement units which are affected by the flood, with 9 settlement units are located at low slope and 1 settlement unit is located at moderate slope. In scenario 3, the settlement units which are affected by the flood are 16, with 13 settlement units are located at low slope and 3 settlement units are located at moderate slope. All the flood depth results are shown in Figure 7-6.

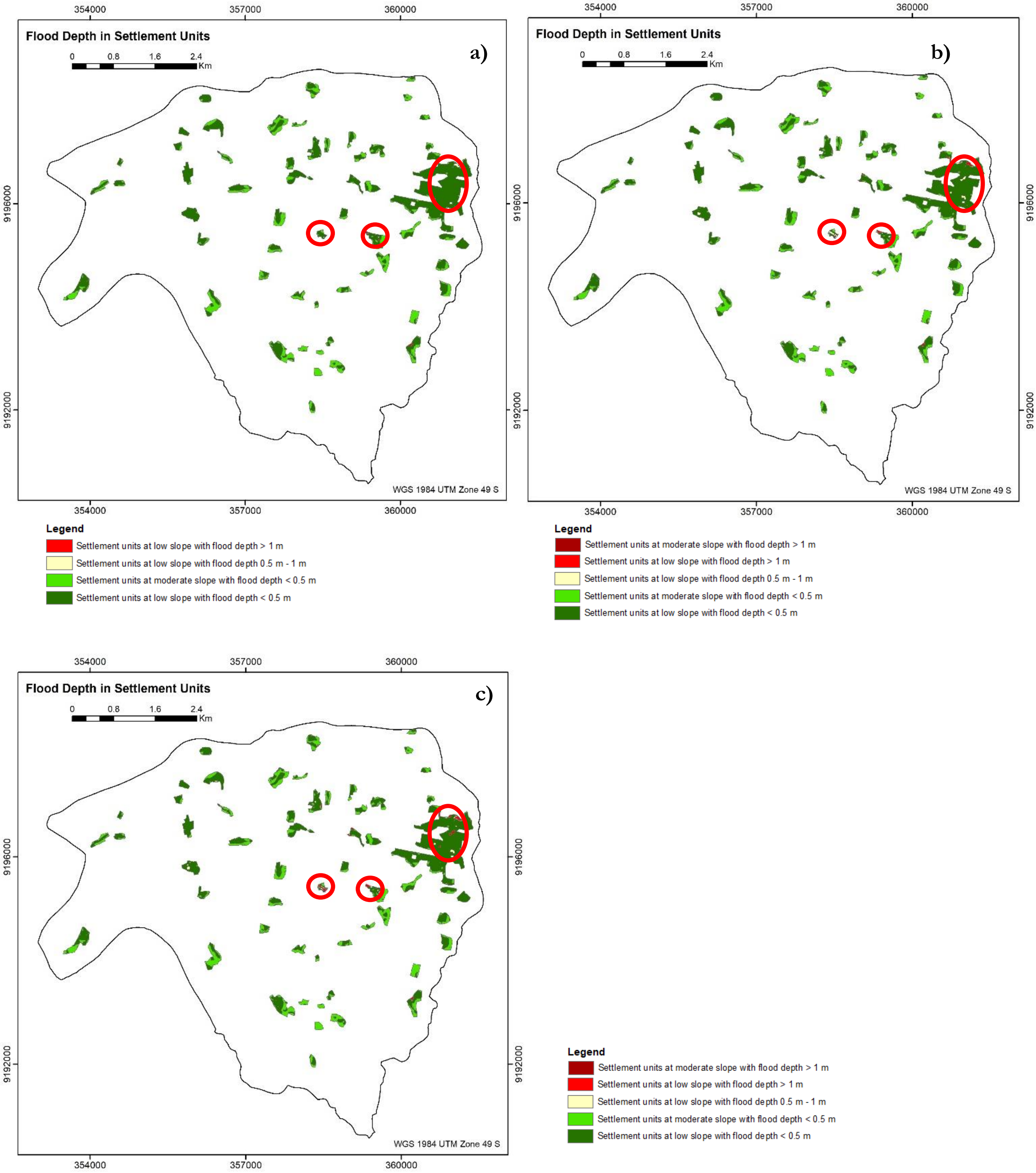


Figure 7-6 The flood depth maps for each settlement units in Karangkobar. (a) is scenario 1, (b) is scenario 2, and (c) is scenario 3. Red circles show the differences for each scenario.

The summaries of the affected settlement units for all hydro-meteorological hazards with different rainfall scenarios in Karangkobar can be seen in Table 7-3.

Table 7-3 The affected settlement units after combining with the modelling with different rainfall scenarios in Karangkobar

No	**Hazard type**		**Rainfall Scenarios**		
			I	**II**	**III**
1	Landslide (SF < 1)	Total number of units affected	26	26	26
		- at low slope	-	-	-
		- at moderate slope	18	18	18
		- at steep slope	8	8	8
		Area affected (m^2)	35,313	35,313	35,313
		Percentage affected (%)	1.2	1.2	1.2
2	Debris flow (height > 1 m)	Total number of units affected	46	46	48
		- at low slope	17	17	19
		- at moderate slope	22	22	22
		- at steep slope	7	7	7
		Area affected (m^2)	162,344	165,313	172,031
		Percentage affected (%)	5.58	5.69	5.92
3	Flood (depth > 1 m)	Total number of units affected	4	10	16
		- at low slope	4	9	13
		- at moderate slope	-	1	3
		- at steep slope	-	-	-
		Area affected (m^2)	6,250	21,406	37,656
		Percentage affected (%)	0.21	0.74	1.30

Based on the results that have been described, the hazard matrix for Karangkobar area can be made. There are many settlement units affected by the slope failure (with the SF < 1), debris flow height, and flood depth. In total, there are 55 settlement units which are affected by the hydro-meteorological hazards. Each settlement unit is not only having one type of hazard but also two or all the hazards. The settlement unit with the ID "Moderate * 24" has all the hazards since scenario 2, and the unit ID "Moderate * 42" has all the hazards in scenario 3. In scenario 3, almost all the settlement units which are located at low slope have two hazard types, debris flow and flood. On contrary, the settlement units which are located at moderate and steep slope have two hazard types, slope failure and debris flow height, from scenario 1 to scenario 3. The hazard matrix for all scenarios in Karangkobar area can be found in annexes 7.

Considering there are no differences for the settlement units which are located in unstable area (SF < 1) between all scenarios, and almost all (24 out of 26) the settlement units that experience the landslide also experience the debris flow height, thus the warning level must be applied to the highest warning level for these settlement units. Based on this warning level, as mentioned in section 4.6, therefore the evacuation should be performed if the rainfall in scenario 1 is exceeded.

The same interpretation also done to the settlement units which are affected by the flood depth and debris flow height. The flood depth mainly affects the settlement units at low slope and moderate slope in scenario 2 and scenario 3. However, the debris flow height also exists in those particular units since scenario 1 and there are no significant differences for all scenarios. Thus, it leads to give the highest warning level to those settlement units, and people who live in those particular settlement units must be evacuated if the rainfall in scenario 1 is exceeded.

8. DISCUSSION AND CONCLUSION

8.1. Discussion

8.1.1. Limitations of The Research

There were several limitations in this research, to be taken into consideration for the evaluation of the results:

1. Fieldwork area selection
   Originally it was decided to do the fieldwork in Karangkobar, but in Indonesia, it was found that there is a field laboratory of the University of Gadjah Mada in Bompon. That second study was preferred for the availability of data needed for modelling in the Open Lisem. While in the field, it was realized that in Bompon, the landslide mainly occurred in cut slopes. Back to the ITC, the quality of the Digital Elevation Model did not permit to analyze for those landslides, so the study area was extended to include Karangkobar with the more severe landslide problems.
2. Availability of data
   - The quality of Digital Elevation Model used for modelling in the study area
   - Limited soil parameter data, especially for Karangkobar area
3. Physical model limitations
   - The new Open Lisem hazard version 1.0 still in development
   - No flexibility in simulating rainfall for many days

8.1.2. Generation of The Homogeneous Unit

The resulting application of r.slopeunits for this study indicates that the quality of the slope unit result depends on the size of the study area and the variation of the elevation as well as the slope angle. Since the main input data is the Digital Elevation Model (DEM), it certainly affects the input parameter definition, such as the minimum area (a) and circular variance (c). Therefore, such definitions are very subjective and site-specific.

Nevertheless, the slope angle variation is the essential factor that influence the slope unit result. As shown in chapter 5, the slope unit result in Bompon looks unrealistic compare to the slope unit in reality. On contrary, the different results are found in Karangkobar. The slope units look more realistic compare to the slope unit from google earth imagery. Although the same DEM used in the modelling, the slope angle variation in this area is much higher than in Bompon.

Alternatively, the generation of the settlement units using a combination of (i) the slope map and (ii) the residential area was applied to the study area. The integration of those factor maps result in the settlement units with different slope angle. Taking into consideration of the landslide occurrences in the study area, particularly in Bompon, where the landslide occurs near or within the residential area, thus, the people in this area are prone to landslide. Therefore, the settlement units have a useful function in term of local early warning. Besides, the settlement unit itself is not as large as the slope units, and it is more focus on the existence of the people as an important element at risk.

8.1.3. Physical Modelling Using Open Lisem

For both study areas, the lack of detail input data influences the model result, and particularly in Bompon, the most important factor that influence the model simulation was the quality of Digital Elevation Model. Cut slope failure could not be modelled without a high spatial resolution DEM. The slope angle derived from DEM is lower than the slope angle in the field, thus makes the model simulation could not provide an accurate slope failure estimation where the dominant failures in the area are cut slope. There are no locations predicted as unstable from the back analysis for the slope instability caused in the rainfalls of 2011 for Bompon, in term of the safety factor result, which is unrealistic. On the other hand, the resulting slope stability model in Karangkobar shows that it has more unstable area than in Bompon. Compared to the slope instabilities that were calculated for Karangkobar for the rainfall event of 2014, it is indicated that the model using the selected input parameters over predicts slope failures. Nevertheless, the performance of a model itself can be increased with calibration and validation data.

Many unavailable data for both study areas lead to the uncertainties of the model results. The soil textures are the main factors to obtain the soil derivatives. Detail soil parameters, for hydrology and geotechnical, mainly were obtained from literature. In addition, although there are the data of soil depth measurements, if they are not distributed well and only a few locations can be measured, it is still required to model the distribution of the soil thickness. In the case of Bompon, the low fitted soil thickness between measured and model influences the model result. In Karangkobar, the soil was obtained from the literature, but the quality was too coarse and also, it assumed the maximum soil thickness in the area was 2 m. The uncertainties related to the numerous parameters that need to be taken into account for the application of this model should also be taken into consideration for interpreting the mismatching of the result with reality. Furthermore, this simulation assumed all the study areas have the same root cohesion, which omitted the root cohesion from different vegetation.

To analyse the stability in Karangkobar using an infinite slope model, in ArcMap, and considering the calculation from equation 1, resulted in safety factor as low as 0.89. Compared to the results from Open Lisem, instability occurs in fewer locations. As I used a beta version of the software Open Lisem, the reliability of the results should be further studied.

There are many factors contribute to the landslide occurrences in Karangkobar. According to Widagdo & Setijadi (2016) the geological condition and the structures in the area are the main control for the landslide occurrences. However, the use of an event-based physical modelling in this study is impossible to predict the landslides which are structurally controlled, as the model itself does not allow to do that. In addition, the landslides in 2014 occurred in the mixed plantation and dry land cultivation (Kristianto et al., 2015) and these data inform that the anthropogenic activities also play a role in the landslide occurrences. It is a bit different from the landslides in Bompon where the settlements are the main land use location for the landslide occurrences.

8.1.4. Application of The Early Warning System Based On Different Rainfall Scenarios

The simulation with different rainfall scenarios in Open Lisem did not work to the result of slope failures (in term of safety factor) for both study areas. With the increasing of rainfall for each scenario which was applied in the modelling gives almost similar safety factor value. It explained that the infiltration model in the Open Lisem only consider the wetting front. In the case for this study, the soil textures for both study areas are dominated by clay which has low saturated hydraulic conductivity, thus makes the infiltration rate in the area also low. Only a little does the wetting front affect the result of slope failures for each different rainfall scenario.

The application of landslide early warning system in Karangkobar for the slope failure and debris flow seems to be exaggerated, and it can be seen from the warning level issued based on the rainfall scenarios. Given rainfall scenario 1, issues the same warning level as rainfall scenario 3. Since the warning level is based on the modelling using rainfall scenarios, the uncertainties related to the parameter and the model software are the main factors that influence the outputs.

8.2. Conclusion

The hydro-meteorological hazard assessment at a local scale by using physical based modelling has been applied in this study with many uncertainties. The purpose of the study is to use the physical model result and combined with the meaningful unit to develop a local landslide early warning system.

The generation of slope units by using r.slopeunits depends on the size of the study area and the variation of the elevation and slope angle. The latter derived from the Digital Elevation Model. Thus, the quality of the DEM actually influences the result of slope units. Nevertheless, in this study, the settlement units with different slope angle classes have more meaningful unit than slope units with respect to the hazard type in the area. The settlement units have more function to the effectiveness in delivering the early warning, because of the high-density people places there.

The landslide in both study areas were influenced by antecedent rainfall. The simulation in Open Lisem cannot include the aforementioned. Therefore, the assumption to use wet condition for making the area already saturated is not a good option. It affects all areas having the same soil condition. Such assumption eventually leads to the over-prediction of the result. In addition, the new Open Lisem could not predict the landslide in Bompon, and on contrary, the over-prediction result comes up in Karangkobar. There are a lot of unstable areas as well as the debris flow height in Karangkobar where this area actually has never been reported about the debris flow occurrences. Two difference result indicates that there are many uncertainties in modelling where it was not only from the input parameters but also from the software that was used for the modelling

There were three rainfall scenario used in the simulation; scenario 1 used the rainfall threshold from Bompon, which is 55 mm, scenario 2 used the 2-year rainfall return period, which is 132 mm, and scenario 3 used the 20-year rainfall return period, which is 206 mm. Scenario 3 is the worst scenario. All scenarios used the same duration in 6 hours. The simulation results reveal that the new Open Lisem could not provide the significant differences for modelling the failures (in term of safety factor) and debris flow height for each rainfall scenario. Only the flood depth shows the significant differences for each scenario.

The integration of the modelling with rainfall scenarios into the settlement units produces the hazard level in each settlement unit. Only one settlement unit is affected by debris flow height in Bompon. On contrary, there are 55 settlement units are affected by failures (with SF < 1), debris flow height, and flood depth in Karangkobar. However, due to no differences results for each scenario, which are the simulation in scenario 1 results in the same impact as the simulation in scenario 3, thus lead to the exaggeration of the warning level.

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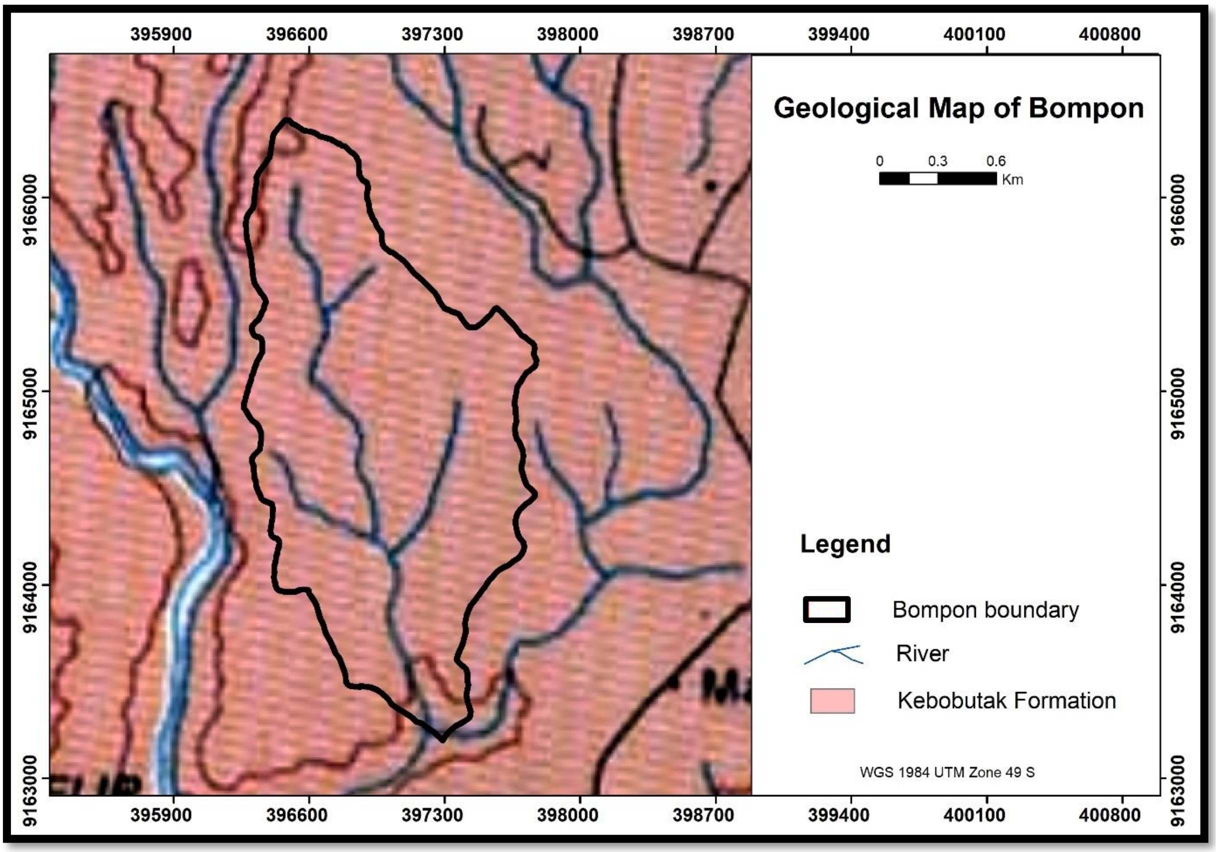
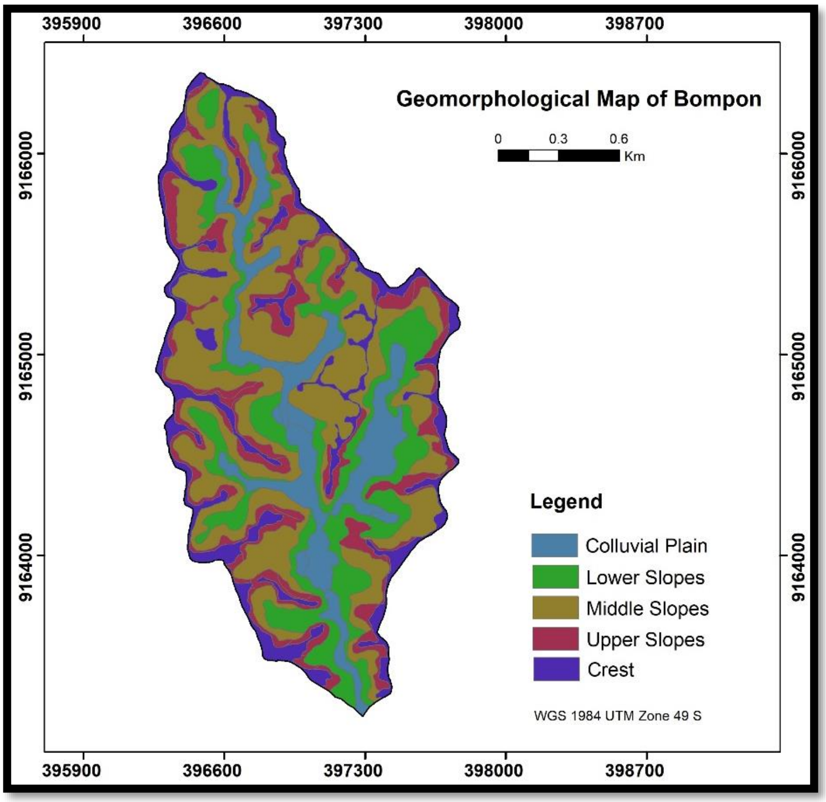
ANNEXES

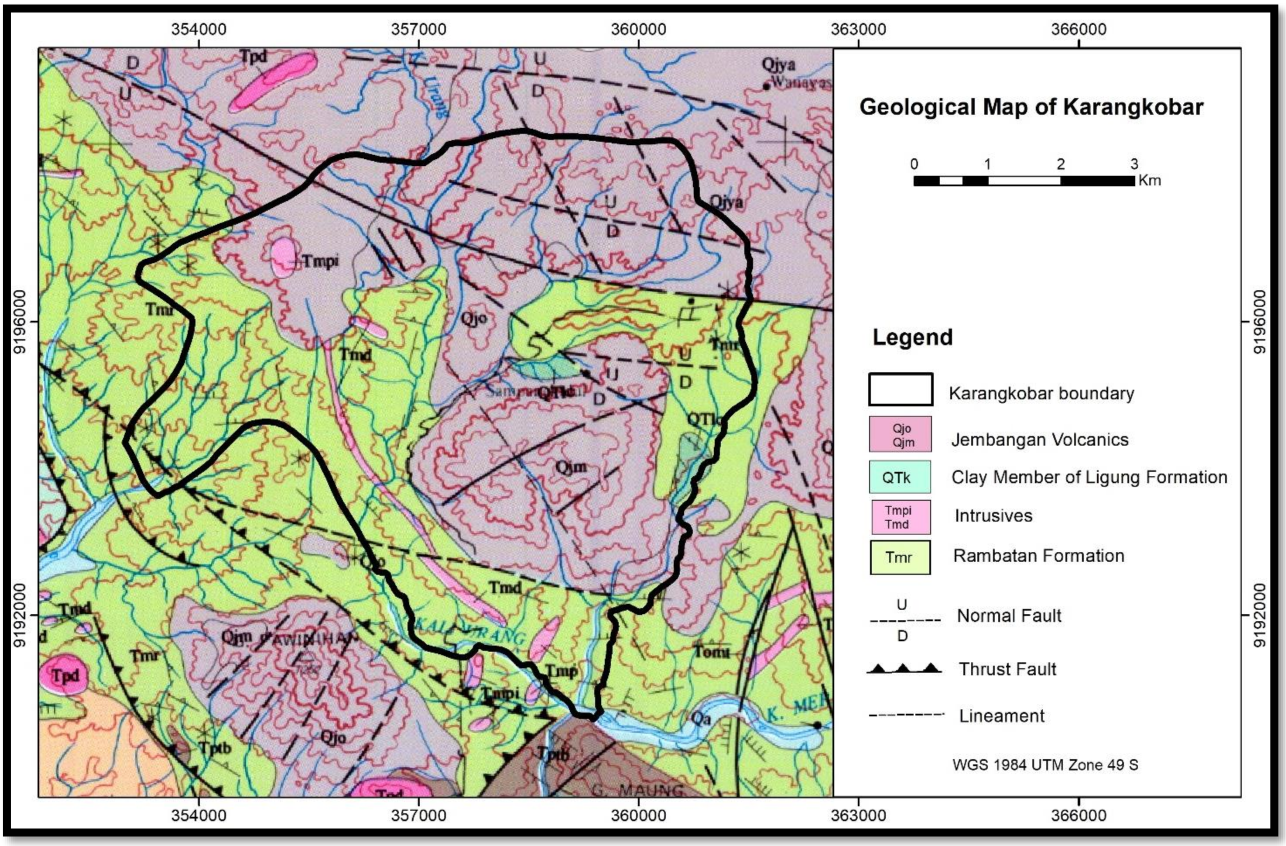
1. Geological Map of Bompon (Rahardjo et al., 1995)



2. Geomorphological Map of Bompon



3. Geological map of Karangkobar (Condon et al., 1996)



4. PCRaster script for data sets input

```
#! --lddin #! --matrixtable
binding

Mask = mask.map;
DEM = dem12.map;
LU = lu.map;
SOIL = soil.map;
NDVI = ndvi.map;
lutable = ludata.tbl;
soiltable = soildata.tbl;

initial

### Preparation
#report mask.map = if(DEM gt -1, scalar(1));

#### HYDROLOGY

#report slope.map = max(0.01,slope(DEM));
#report grad.map = max(0.01,sin(atan(slope(DEM))));
#report ldd.map = lddcreate(DEM,1e31,1e31,1e31,1e31);
#report accuflux.map = accuflux(ldd.map,1.0);
#report streamorder.map = streamorder(ldd.map);
#report channelmask.map = scalar(if(streamorder.map gt 4,1.0,0.0));
```

```
#report lddchannel.map = lddcreate(if(channelmask.map eq 1,DEM),1e31,1e31,1e31,1e31);
#report channelgrad.map = sin(atan(slope(if(channelmask.map eq 1,DEM))));
#report channelwidth.map = max(0.1,channelmask.map * (0.2 + 4.5 * (accuflux.map - 750)/(18700)));
#report channeldepth.map = max(0.1,channelmask.map * (0.1 + 3 * (accuflux.map - 750)/(18700)));
#report curvature.map = profcurv(DEM);
#report channeldist.map = spread(nominal(channelmask.map),0.0,1.0);
#report outlets.map = pit(ldd.map);

#### LAND USE

#report n.map = lookupscalar(lutable,1,LU);
#report ch.map = lookupscalar(lutable,2,LU);
#report rr.map = lookupscalar(lutable,3,LU);

#report vegc.map = (NDVI/mapmaximum(NDVI));
#lai = ln(1-vegc.map)/-0.4;
#report lai.map = if(vegc.map gt 0, lai/vegc.map, 0);

#### SOIL

#report ksat.map = lookupscalar(soiltable,1,SOIL);
#report psi.map = lookupscalar(soiltable,2,SOIL);
#report thetar.map = lookupscalar(soiltable,3,SOIL) / 100;
#report thetas.map = lookupscalar(soiltable,4,SOIL) / 100;
#report soildensity.map = lookupscalar(soiltable,5,SOIL) * 1000;
#report coh.map = lookupscalar(soiltable,6,SOIL);
#report soilifa.map = lookupscalar(soiltable,7,SOIL) * 3.14/180;
#report grainsize.map = lookupscalar(soiltable,8,SOIL);
#report rocksize.map = lookupscalar(soiltable,9,SOIL);
#report d50.map = lookupscalar(soiltable,10,SOIL);
#report d90.map = lookupscalar(soiltable,11,SOIL);
#report rockfraction.map = lookupscalar(soiltable,12,SOIL);
#report cohadd.map = lookupscalar(soiltable,13,SOIL);
#report thetai.map = thetar.map + 0.80 * (thetas.map - thetar.map);
#report channelcoh.map=coh.map*channelmask.map;
#report chanman.map=n.map*channelmask.map;
#report chanside.map= scalar(if(channelmask.map ne 0, 0));

# soildepthtest.map = 4.5 - 0.0008 * dem12.map - 0.7 * abs(slope.map) - 0.001 * channeldist.map + 79 * curvature.map;
```

5. Landslide Inventory in Bompon

No	Coordinate		Exposure Element	Time			Location	
	X	Y		Day	Month	Year	Village	Hamlet
1	397406	9164034	Settlements	21	December	2011	Margoyoso	Tubansari
2	397393	9163803	Road	21	December	2011	Margoyoso	Kalisari
3	397332	9164093	Settlements	21	December	2011	Margoyoso	Tubansari
4	397310	9164134	Rice field	-	-	-	Margoyoso	Tubansari
5	397590	9164198	Mixed plantation	-	-	-	Margoyoso	Tubansari
6	397152	9163451	Mixed plantation	21	December	2011	Margoyoso	Kalisari
7	397154	9163407	Settlements	21	December	2011	Margoyoso	Kalisari
8	397242	9163408	Road, settlements	-	-	-	Margoyoso	Kalisari
9	397328	9163383	Settlements	-	-	2011	Margoyoso	Kalisari
10	397405	9163394	Settlements	-	-	2011	Margoyoso	Kalisari
11	397157	9164266	River, rice field	-	-	-	Margoyoso	Tubansari
12	397264	9164200	River	-	-	-	Margoyoso	Tubansari
13	397435	9164397	River, rice field	-	-	-	Wonogiri	Tuanan
14	397301	9164591	River, rice field	-	-	-	Wonogiri	Bleber
15	396963	9163858	River, rice field	-	-	2015	Margoyoso	Kalisari
16	396673	9165281	Road	-	-	-	Wonogiri	Bompon
17	396808	9165304	Settlements	-	-	-	Wonogiri	Sabrang
18	397365	9165170	Settlements	-	-	-	Wonogiri	Ngemplak
19	396662	9164707	Road, settlements	-	-	-	Wonogiri	Bleber
20	396617	9164666	Mixed plantation	-	-	-	Wonogiri	Bleber
21	397328	9163786	Settlements	-	-	2011	Margoyoso	Kalisari
22	397481	9164459	Rice field	-	-	-	Wonogiri	Tuanan
23	397204	9164451	Mixed plantation	-	-	-	Wonogiri	Bleber
24	396388	9165194	Settlements	-	-	-	Wonogiri	Bompon
25	397469	9164477	Rice field	-	-	-	Wonogiri	Tuanan

6. Landslide Inventory in Karangkobar

No	Coordinate			Mechanism	Material type	Location	Date
	X	Y	Z				
1	357402	9197682	-	-	-	-	16-Dec-14
2	360590	9197171	1040	Luncuran	Tanah	Desa Leksana	9-Mar-16
3	358019	9196712	1026	Luncuran	Tanah	Desa Ambal	2-Mar-16
4	356904	9196392	978	Jatuhan	Batuan	Desa Karanggondang	9-Mar-16
5	354322	9196379	951	Rayapan	Tanah	Desa Karanggondang	20-24 February 2016
6	359716	9196079	1018	Rayapan	Tanah	Desa Karanggondang	13-Dec-14
7	357603	9195447	940	Jatuhan	Batuan	Desa Ambal	6-Mar-16
8	361187	9195373	993	Rayapan	Tanah	Desa Karangkobar	12-Dec-14
9	358802	9194958	-	-	-	Desa Sampang	12-Dec-14
10	360737	9194626	889	Luncuran	Tanah	Desa Purwodadi	Jan-16
11	359231	9194648	-	-	-	-	-
12	358542	9194593	-	-	-	-	-
13	360426	9194323	977	Jatuhan	Batuan	Desa Purwodadi	5-Mar-16
14	356248	9193624	825	Campuran	Tanah dan Batuan	Desa Pagerpelah	20-Dec-14
15	357424	9193507	896	Rayapan	Tanah	Desa Slatri	12-Dec-14
16	360230	9192939	918	Luncuran	Tanah	Desa Gumelar	12-15 December 2014
17	360149	9192836	926	Campuran	Batuan	Desa Gumelar	12-Dec-14
18	356949	9192436	883	Campuran	Tanah dan Batuan	Desa Paweden	13-Dec-14
19	358399	9192565	777	Luncuran	Tanah	Desa Paweden	12-Dec-14
20	359231	9194648	-	-	-	-	Dec-14

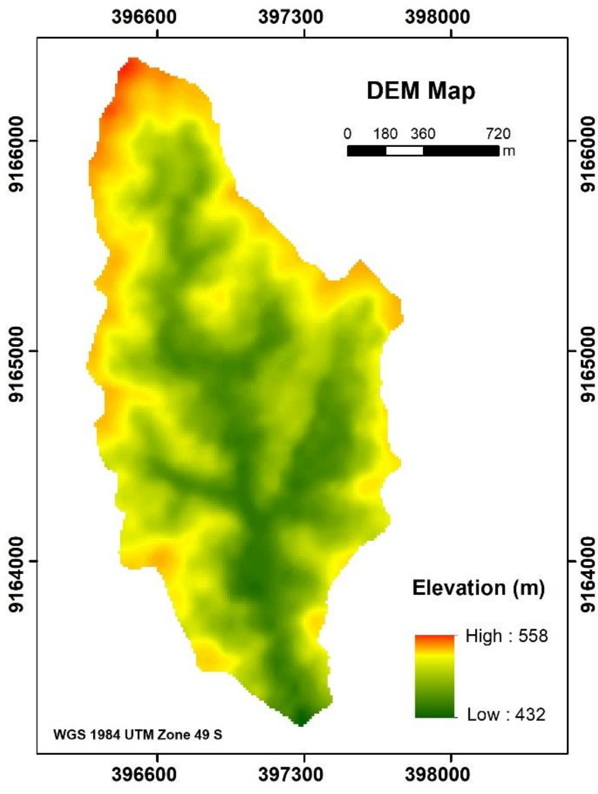
7. Hazard matrix in Karangkobar

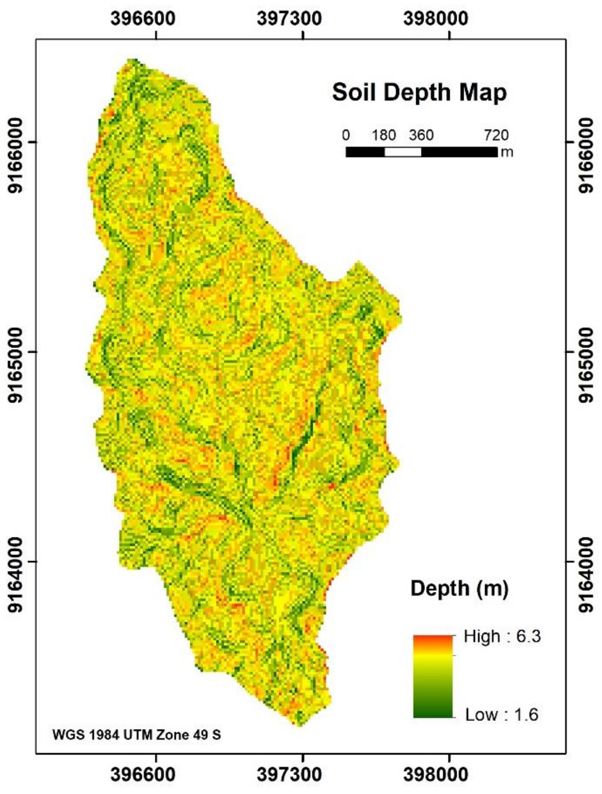
Scenario 1			
Unit ID	Landslide	Debris flow	Flood
Low * 1	-	-	-
Low * 10	-	-	-
Low * 11	-	x	x
Low * 14	-	x	-
Low * 2	-	x	-
Low * 21	-	x	-
Low * 28	-	-	-
Low * 29	-	x	-
Low * 3	-	x	-
Low * 33	-	-	-
Low * 34	-	-	-
Low * 35	-	x	-
Low * 36	-	x	x
Low * 37	-	x	x
Low * 38	-	x	-
Low * 4	-	x	-
Low * 46	-	x	-
Low * 49	-	x	-
Low * 51	-	x	-
Low * 57	-	x	-
Low * 6	-	x	x
Low * 8	-	x	-
Moderate * 10	-	-	-
Moderate * 11	x	x	-
Moderate * 14	-	x	-
Moderate * 18	x	x	-
Moderate * 23	x	x	-
Moderate * 24	x	x	-
Moderate * 3	-	x	-
Moderate * 34	x	x	-
Moderate * 35	x	x	-
Moderate * 36	x	x	-
Moderate * 37	x	x	-
Moderate * 38	-	x	-
Moderate * 4	x	x	-
Moderate * 42	x	x	-
Moderate * 46	-	-	-
Moderate * 47	x	-	-
Moderate * 5	x	x	-
Moderate * 50	-	x	-
Moderate * 51	x	x	-
Moderate * 52	-	x	-
Moderate * 56	x	x	-
Moderate * 57	x	x	-
Moderate * 6	x	x	-
Moderate * 7	x	x	-
Moderate * 8	x	x	-
Steep * 18	x	x	-
Steep * 34	x	x	-
Steep * 35	x	x	-
Steep * 4	x	x	-
Steep * 51	x	x	-
Steep * 56	x	-	-
Steep * 57	x	x	-
Steep * 6	x	x	-

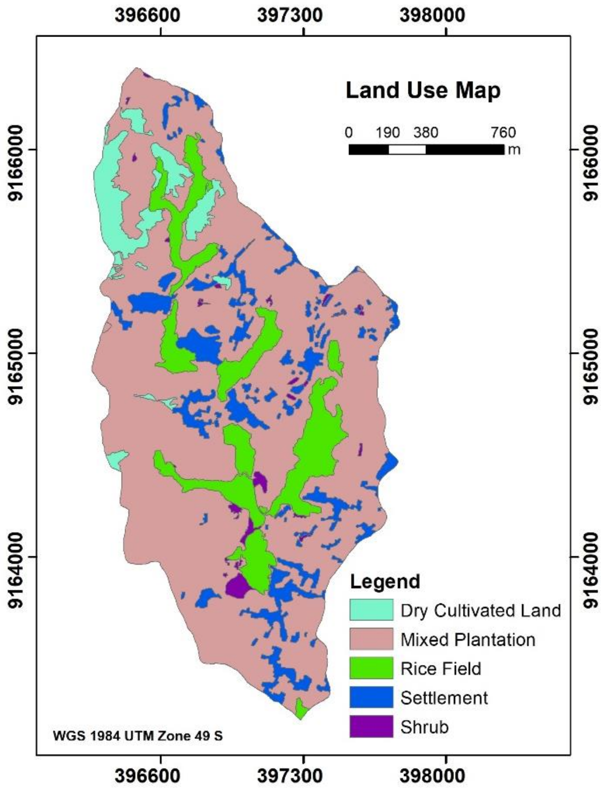
Scenario 2			
Unit ID	Landslide	Debris flow	Flood
Low * 1	-	-	-
Low * 10	-	-	x
Low * 11	-	x	x
Low * 14	-	x	-
Low * 2	-	x	x
Low * 21	-	x	-
Low * 28	-	-	x
Low * 29	-	x	x
Low * 3	-	x	-
Low * 33	-	-	-
Low * 34	-	-	-
Low * 35	-	x	-
Low * 36	-	x	x
Low * 37	-	x	x
Low * 38	-	x	x
Low * 4	-	x	-
Low * 46	-	x	-
Low * 49	-	x	-
Low * 51	-	x	-
Low * 57	-	x	-
Low * 6	-	x	x
Low * 8	-	x	-
Moderate * 10	-	-	-
Moderate * 11	x	x	-
Moderate * 14	-	x	-
Moderate * 18	x	x	-
Moderate * 23	x	x	-
Moderate * 24	x	x	x
Moderate * 3	-	x	-
Moderate * 34	x	x	-
Moderate * 35	x	x	-
Moderate * 36	x	x	-
Moderate * 37	x	x	-
Moderate * 38	-	x	-
Moderate * 4	x	x	-
Moderate * 42	x	x	-
Moderate * 46	-	-	-
Moderate * 47	x	-	-
Moderate * 5	x	x	-
Moderate * 50	-	x	-
Moderate * 51	x	x	-
Moderate * 52	-	x	-
Moderate * 56	x	x	-
Moderate * 57	x	x	-
Moderate * 6	x	x	-
Moderate * 7	x	x	-
Moderate * 8	x	x	-
Steep * 18	x	x	-
Steep * 34	x	x	-
Steep * 35	x	x	-
Steep * 4	x	x	-
Steep * 51	x	x	-
Steep * 56	x	-	-
Steep * 57	x	x	-
Steep * 6	x	x	-

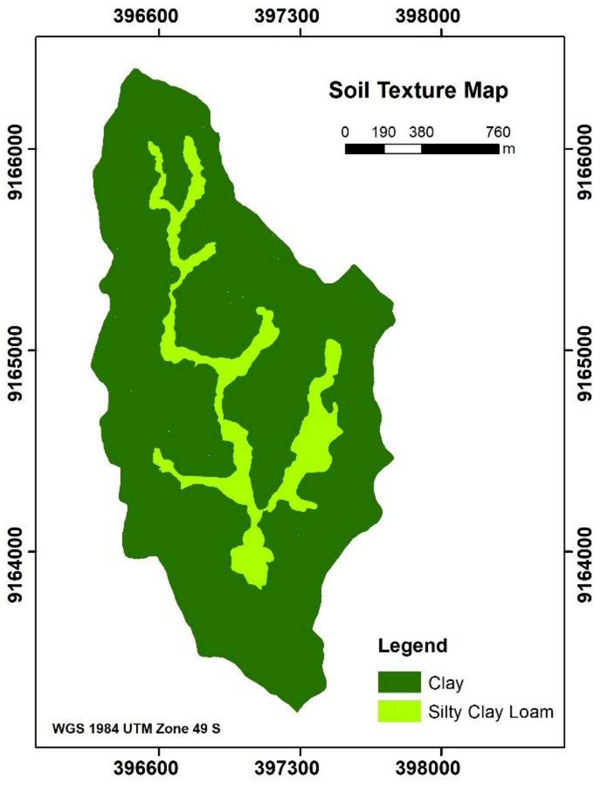
Scenario 3			
Unit ID	Landslide	Debris flow	Flood
Low * 1		-	x
Low * 10		-	x
Low * 11	-	x	x
Low * 14	-	x	x
Low * 2	-	x	x
Low * 21	-	x	-
Low * 28		-	x
Low * 29	-	x	x
Low * 3	-	x	-
Low * 33	-	x	x
Low * 34	-	x	-
Low * 35	-	x	-
Low * 36	-	x	x
Low * 37	-	x	x
Low * 38	-	x	x
Low * 4	-	x	-
Low * 46	-	x	-
Low * 49	-	x	-
Low * 51	-	x	-
Low * 57	-	x	-
Low * 6	-	x	x
Low * 8	-	x	x
Moderate * 10	-	-	x
Moderate * 11	x	x	-
Moderate * 14	-	x	-
Moderate * 18	x	x	-
Moderate * 23	x	x	-
Moderate * 24	x	x	x
Moderate * 3	-	x	-
Moderate * 34	x	x	-
Moderate * 35	x	x	-
Moderate * 36	x	x	-
Moderate * 37	x	x	-
Moderate * 38	-	x	-
Moderate * 4	x	x	-
Moderate * 42	x	x	x
Moderate * 46	-	-	-
Moderate * 47	x	-	-
Moderate * 5	x	x	-
Moderate * 50	-	x	-
Moderate * 51	x	x	-
Moderate * 52	-	x	-
Moderate * 56	x	x	-
Moderate * 57	x	x	-
Moderate * 6	x	x	-
Moderate * 7	x	x	-
Moderate * 8	x	x	-
Steep * 18	x	x	-
Steep * 34	x	x	-
Steep * 35	x	x	-
Steep * 4	x	x	-
Steep * 51	x	x	-
Steep * 56	x	x	-
Steep * 57	x	x	-
Steep * 6	x	x	-

8. Input maps for Open Lisem (Bompon area)

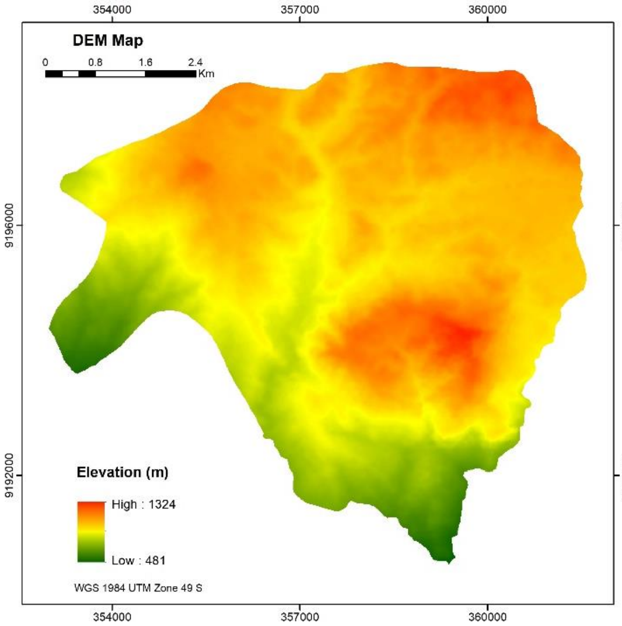


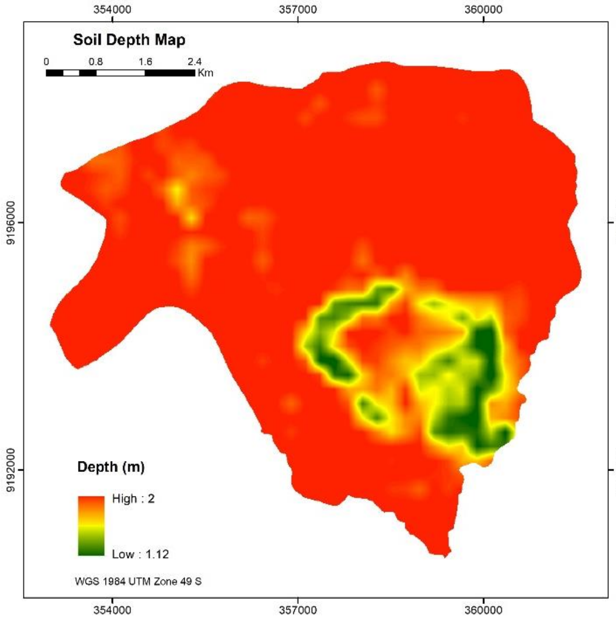


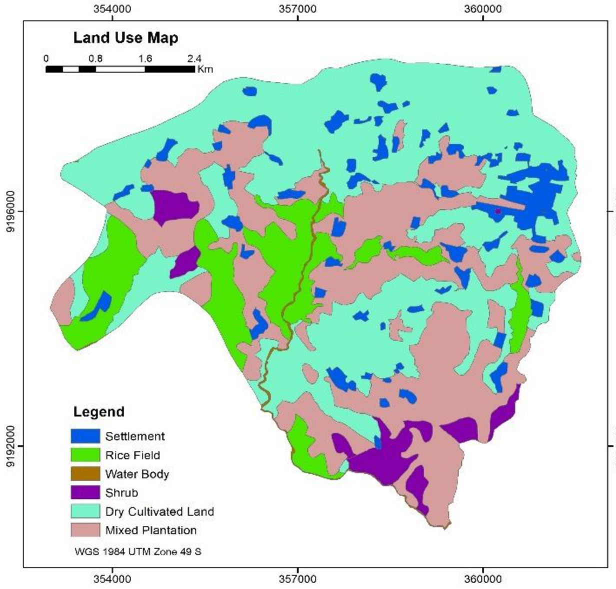


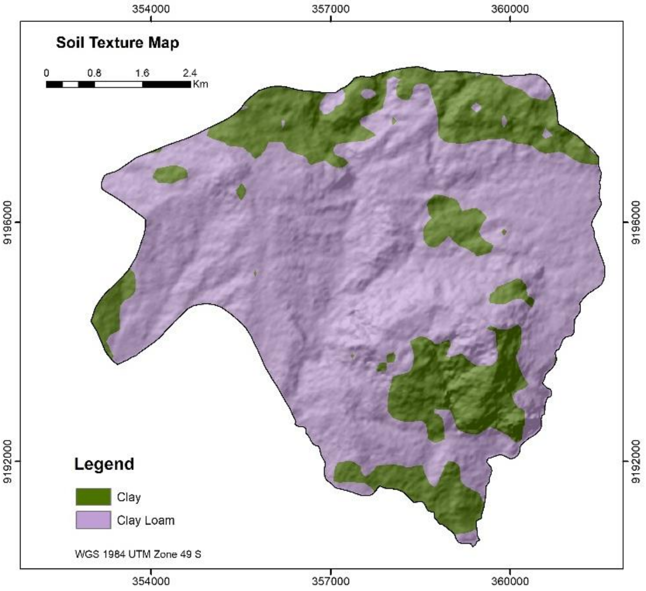


9. Input maps for Open Lisem (Karangkobar area)









10. Landslide Susceptibility Zone Map (Center for Volcanology and Geological Hazard Mitigation, Bandung, Indonesia)