Hydrological – Slope Stability Modeling for Landslide Hazard Assessment by means of GIS and Remote Sensing Data

A case study of Probolo sub-catchments, Gesing sub-district
Purworejo Regency, Indonesia

Thesis submitted to the Graduated School, Faculty of Geography, Gadjah Mada University in partial fulfillment of the requirement for the degree of Master of Science in Geo-Information for Spatial Planning and Risk Management

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THESIS

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Dedicated to My Beloved Mother

DISCLAIMER

This document describes work undertaken as part of a program of study at the Double Degree International Program of Geoinformation for Spatial Planning and Disaster Risk Management, a Joint Program of ITC the Netherland and UGM, Indonesia. All views and opinions expressed therein remain the sole responsibility of the author, and do not necessarily represent those of the institute.

Christanto, N

ABSTRACT

Landslides are main natural hazards occurring on mountainous area situated in the wet tropical climate like in Indonesia. The study area, Probolo Sub Catchments, as a part of Menoreh Mountains is one of representative example of Indonesian region facing landslides problem. Several catastrophic landslides induced by rainfall are every year reported from different parts of Probolo sub-catchments.

This study attempted to simulate slope stability in Probolo sub-catchments using deterministic modeling by means of PC Raster® simulation. Coupled models of STARWARS and PROBSTAB were used in this research in order to simulate the dynamic of slope stability (van Beek 2002 and Sekhar 2006). The slope stability modeling was based on infinite method. In order to run these models, high precision and resolution of DEM were needed. Hence, the combination between topographic map, DGPS measurement and Laser scanning survey were carried. Volumetric moisture content and groundwater level were simulated from STARWARS model while the PROBSTAB simulated the slope stability and probability of failure. Sensitivity analysis was applied to evaluate the model.

The result of hydrological sensitivity analysis shows that soil depth was the most sensitive parameters. For the slope stability modeling, the most sensitive parameter was slope and followed by friction angle and cohesion. Overall slope stability simulation shows that the area categorized as unstable, critical and stable are 11.32%, 31.86% and 56.82% respectively. Model validation, done by using Yin and Yan equation shows that the accuracy of the model reached 20.5 %. This poor result of model was probably caused by the poor quality of input data and field observation. How ever, the results of dynamic modeling are ideal for landslide hazard assessment. Dynamic modeling software such as PC Raster® that are open source and free software are reliable alternatives to others commercial software.

Key words: Dynamic modeling, landslide hazard assessment, PC Raster®, STARWARS, PROBSTAB.

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1 Introduction

1.1 Background

Landslides are one of the hazardous phenomena. They create negative impacts include loss of life, property damage and permanent landscape change. Landslides are defined as the movement of a mass of rock, debris or earth down a slope (Cruden, 1991). The occurrence of these extreme phenomena cannot be averted, but understanding these hazards can lead to proper mitigation strategies and thus significantly reduce their impacts (Daag, 2003). Landslides usually occur in hilly or mountainous areas with low slope stability. Slope stability can be influence by many variables such as climate factors and terrain factors. All variable are interrelated and create a complex system. In this situation, a model is needed in order to simplify the complex system.

Indonesia has many hilly topography and mountainous areas. These conditions can contribute to the high landslide susceptibility. Due to the humid tropical climate, the annual precipitation is known as the most triggering factor of landslides. Most landslides in Indonesia are triggered by rainfall, increase in ground water level, or earthquakes. They can occur in any terrain given the right conditions of soil moisture, and the angle of slope. From the statistical data of fatalities by country, it can conclude that Indonesia was the most affected countries due to the landslide disaster after China (ILC, 2004), Figure 1. The total number of fatalities recorded by International Landslide Centre University of Durham UK for 2003 shows that in Indonesia has 441 fatalities cases, this number was relatively high compared with five years before.

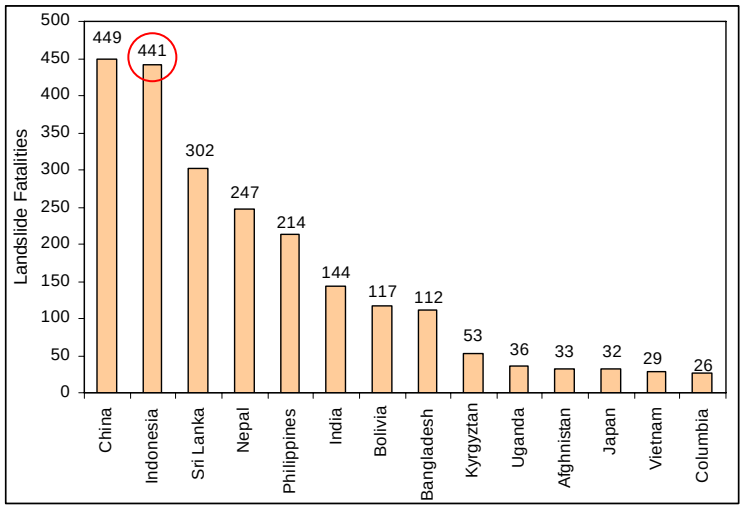

Figure 1 Landslide fatalities statistic data from ILC, 2004.

Mount Menoreh was known as one of the prone area to landslides in Indonesia. Every year during intense rainfall periods, several incidences of landslides are reported from part of Mount Menoreh, Central Java, Indonesia. Landslide in Mount Menoreh also caused a large number of victims and huge losses both from direct or indirect loss (Table 1).

In December 2005 the Sigebang landslide caused damages to the settlements and builds a landslide dam. Due to this landslide, 5 building were totally damage and 1 person was killed. From this background, the research of modeling slope stability in Probolo sub-catchments is

important. The landslide dam created a lake and during 1, 5 days the landslide dam collapse (Figure 2).

Table 1 Statistical data of landslide in part of mount Menoreh, Central Java, Indonesia

Date	No	Location	No of Family affected	Economic Loss (in IDR)	Emergency Respond
1999					
12/11/1999	1	Tritis, **Ngargosari**	1	6,050,000	
2000					
12/11/2000	1	Petet, **Ngargosari**	2	1,100,000	
26/11/2000	1	Trayu	1	1,050,000	
11/12/2000	7	Plarangan, **Purwoharjo**	3	8,500,000	
		Sendangrejo	1	1,000,000	
		Bangunrejo	1	3,500,000	
		Junut	1	3,500,000	
19/12/2000	2	Pagutan, **Purwoharjo**	2	1,700,000	
		Kaliduren, **Kebonharjo**	1	1,250,000	
Total	11		12	21,600,000	
2001					
20/10/2001	8	Keceme, **Gerbosari**	7	12,500,000	
		Kayugede	1	2,500,000	
21/10/2001	2	Keceme, **Gerbosari**	1	1,500,000	
		Clumprit	2	3,500,000	
		Tulangan, **Ngargosari**	1	2,350,000	
		Tegalsari	1	4,150,000	
		Pucung	1	5,120,000	
		Pagutan, **Purwoharjo**	1	1,500,000	
		Jeringan, **Kebonharjo**	1	500,000	
		Kedunggupit	1	100,000	
		Jarakan	1	800,000	
		Pelem	3	2,700,000	
22/10/2001	8	Pucung, **Ngargosari**	1	5,120,000	
		Jarakan, **Kebonharjo**	2	1,300,000	
		Gowok	4	12,500,000	Relocation
		Balong VI, **Banjarsari**	2	4,200,000	
		Ngaran	1	270,000	
		Kaliwungklon	1	1,250,000	
		Plono Barat, **Pagerharjo**	1	3,000,000	Relocation
		Plono Timur	1	700,000	
06/11/2001	1	Ngaliyan, **Ngargosari**	2	2,750,000	
20/11/2001	8	Kedungrong, **Purwoharjo**	11	171,025,000	Relocation
		Duwet	9	86,000,000	Relocation Transmigration
		Sendangrejo	1	1,550,000	
		Besole	1	2,500,000	
		Junut	1	1,500,000	
		Balong V, **Banjarsari**	1	10,000,000	
Total	27		60	340,885,000	

Date	No	Location	No of family affected	Economic Loss (in million of Rp)	
2002					
14/O2/2002	1	Taman, **Purwoharjo**	2	5,000,000	Relocation
18/03/2002	1	Keceme, **Gerbosari**	1	3,000,000	
17/04/2002	1	Kaliduren, **Kebonharjo**	1	1,850,000	
01/11/2002	2	Beteng, **Pagerharjo**	1	6,000,000	
		Kalinongko	1	1,500,000	
25/12/2002	2	Jeringan, **Kebonharjo**	2	2,520,000	
		Madigondo, **Sidoharjo**	1	5,250,000	
Total	7		9	25,200,000	
2003					
04/01/2003	4	Pelem, **Kebonharjo**	2	5,000,000	
		Gowok	1	4,000,000	
		Manggis, **Gerbosari**	1	1,525,000	
		Nguntuk-untunk, **Ngargosari**	1	3,400,000	
05/01/2003	1	Tegalsari, **Ngargosari**	2	2,500,000	
Total	5		7	16,425,000	

Source: Purworejo Hazard Information, 2003

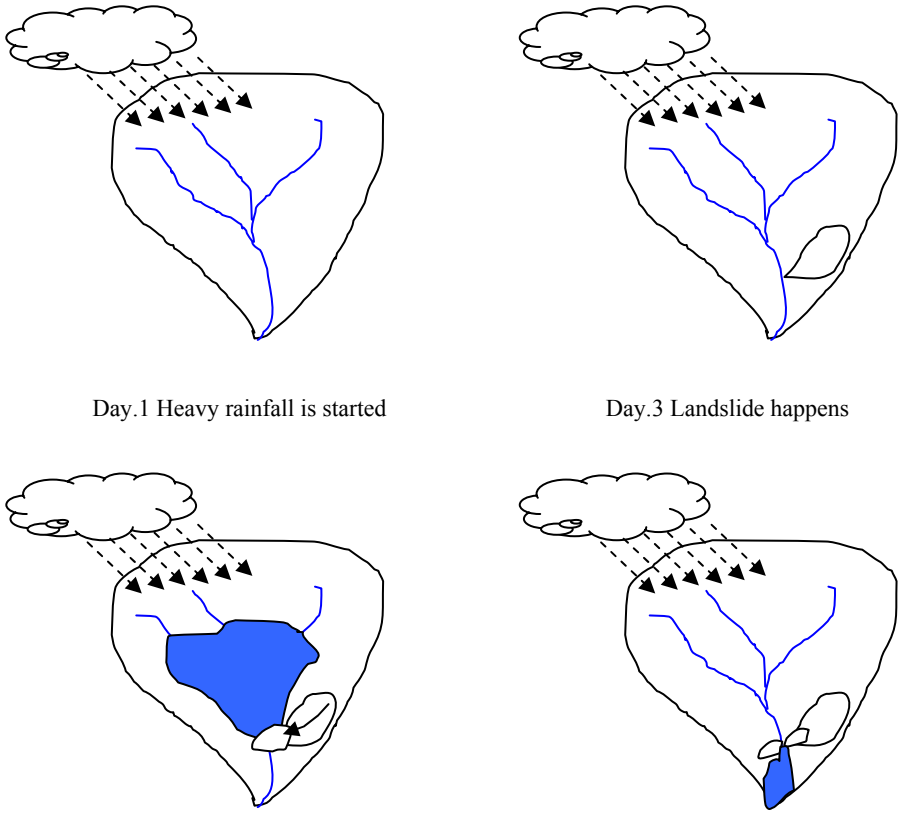

Figure 2 Sigebang landslide processes

1.2 Problem Definition

Probolo sub-catchments were situated in a hilly area. As part of Mount Menoreh, Probolo sub-catchments frequently face problems due to landslides. Every year several incidences of landslides induced by rainfall and related victims are reported from different parts of Probolo sub-catchments.

There have been many studies conducted in Mount Menoreh related to landslide problems (Hadmoko 2004, Bachri 2005, Marhaento 2006). They assess the susceptibility of landslide using geomorphologic approach, statistical models and deterministic models.

How ever, the researches on a dynamic modeling for landslide assessment have not done yet in this area. The result on dynamic modeling is actually valuable input for spatial planning to reduce the damage. Landslide disaster reduction processes will need a lot of information such as, maps, and furthermore the information of probability of occurrence in terms of space and time. To assess that information, dynamic modeling seems to be the best way. Using models we can assess the hazard information by simplification of reality. There for, the research on dynamic modeling was actually needed in this area. The aim of this study is to model the slope stability of Probolo sub-catchments using PC Raster simulation for landslide hazard assessment.

1.3 Objective and Research Question

1.3.1 Objective

The objective of this research was to find out the slope stability of Probolo sub-catchments using PC Raster simulation. In order to achieve that objective, the following modeling and analysis will be done:

1. Hydrological Modeling using STARWARS script,
2. Slope stability modeling using PROBSTAB script,

Specific Objectives

Slope stability modeling

- Generate DEM Topographic Map, Aerial Photo Interpretation, DGPS and Laser survey
- Land use interpretation of Aerial Photograph, PGIS and Field Investigation
- Sub catchments hydrological modeling using PC Raster (STARWARS)
- Perform slope stability modeling using PC Raster (PROBSTAB)

1.3.2 Research Question

1. What data needed to perform Slope Stability modeling in PC Raster environment?
2. Is it possible to derive a DEM from DGPS measurement in combined with contour maps?
3. Which other area nearby might have the slope stability problem?
4. Is dynamic modeling such as PC Raster® simulation relevant for providing information as an input in spatial planning in Mounts Menoreh?
5. How to carry out sensitivity analysis to evaluate the models?
6. How reliable and accurate the PC raster model for slope stability assessment?

1.4 Literature Review

1.4.1 Landslide

Landslides are defined as the movement of a mass of rock, debris or earth down a slope (Cruden, 1991). Although the term of landslide only used especially for the one of type of mass movement occurring along well-defined sliding surface, it also used as the most general term for all mass movement including those that involve little or no sliding (Van Westen, 1993). Varnes (1978) was classified the type of mass movement intio eight types i.e. (a) creep, (b) landslide, (c) slump, (d) topples, (e) lateral spreading, (f) flow (mudflow and earthflow), (g) rockfall and (h) complex (the combination of various landslides). Varnes (1978), Carson and Kirby (1972) classified the landslide type based on two criteria i.e. (a) the velocity of the movement (slower to faster) and (b) the water content of earth material of landslides (drier to wetter). The classification of landslides type based on Carson and Kirby criteria are shown as triangle system in Figure 3 and field view in Figure 4. Other classification of landslide created by Hutchinson (1968) in the Cook and Doornkamp (1990), this classification based on the existence of the slip surface they are (a) translational slide, when position of slip surface is perpendicular with surface material, (b) rotational slide, when the slip surface position is formed by the circular form and the material movement is rotational slide and (c) rock fall when the material movement without slip surface.

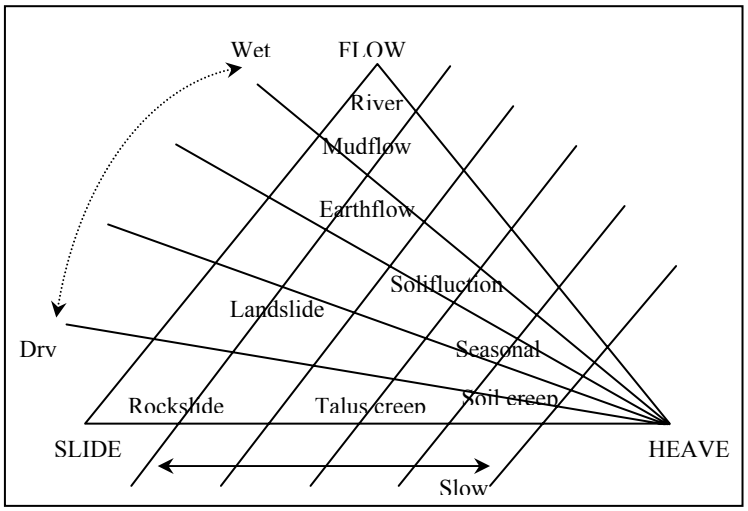

Figure 3 Triangle System Classification of Landslide Type (Carson and Kirby, 1972)

The main factors which influence landslides are discussed in Varnes (1984) and Hutchinson (1988). Normally the most important factors are bedrock geology (lithology, structure, degree of weathering), geomorphology (slope gradient, aspect, and relative relief), soil (depth, structure, permeability, and porosity), land use and land cover, and hydrologic conditions. Many factors influence the development of landslides, and particular slide can seldom be attributed to single factor; however it may be possible to identify the main factor controlling landslide. Theoretically, the landslide process can be occurred as the result of the disturbance of slope equilibrium. The disturbance of equilibrium of the slope is caused by the increasing of the shear stress and the decreasing of the shear strength. Selby, 1991 classified two major factor contributing to the landslide i.e. (a) the factor contributing to high shear stress i.e. removal of lateral support (stream water, weathering, slope increasing), overloading (rain, soil saturated,

fills), and lateral pressure (swelling of clay, water in interstices) and (b) the factor contributing to low shear strength i.e. composition and texture (weak material, uniform grain size, smooth grain shape), physical-chemical reaction, effect of pore water pressure, structure changes, and relics structures (joint and cracking). These factor described above are the common factor which used to analyze the landslide process and hazard (Selby, 1991).

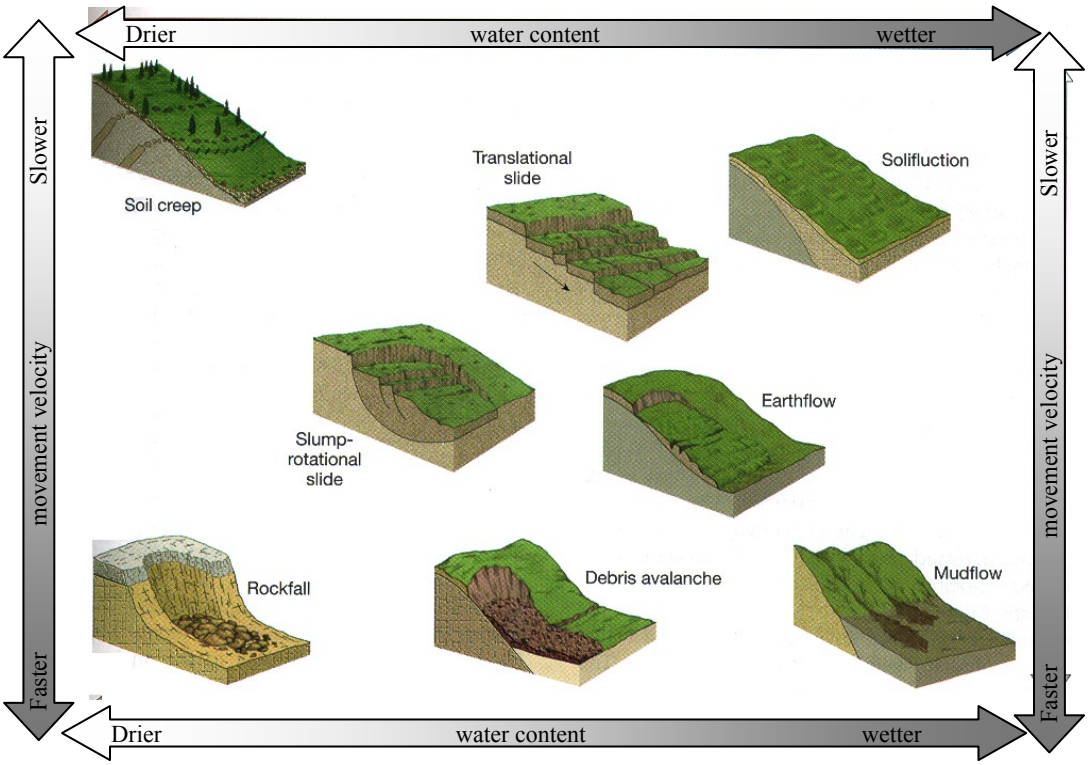

Figure 4 The field-view of the landslide type (Carson and Kirby, 1972).

1.4.2 GIS for Landslide Hazard Zonation

A Geographic Information System (GIS) is a set of powerful tools for collecting, storing, retrieving, transforming, analyzing, and displaying spatial data from the real world for a particular set of purposes (Burrough, 1986). GIS provides strong functions both in geo-statistical analysis and database processing. In addition, the extension of the analysis to include environmental impact assessment of a slope failure can be easily and effectively performed using GIS.

From a survey of recent GIS applications to slope failure hazard zonation, it is found that most research has concentrated on statistical methods in order to determine quantitative relationships between slope failure and influential factors while GIS has been used to perform regional data preparation and processing (Zhoua G *et al,* 2003). Van Westen (1993) used GIS as the main tool to build the landslide database and their factor influenced, to analyze the landslide hazard within various model and various scale. The model which be used are statistical landslide hazard analysis, frequency landslide hazard analysis, deterministic landslide hazard analysis. Deterministic landslide hazard analysis have performed within two triggering mechanisms e.g. rainfall and seismic acceleration. Terlien (1996) used GIS as a main tool to model the spatial

deterministic landslide hazard zonation by using combination of various data such as rainfall data, engineering geological data and hydrological data of his study area. From his study can be concluding that GIS can be integrated within non-spatial mathematical model (in this case infinite slope stability model) to model the spatial condition of landslide hazard and identify the triggering mechanism. Dai (2001) studying on the use of a Geographical Information Systems (GIS) database, compiled primarily from existing digital maps and aerial photographs, to describe the physical characteristics of landslides and the statistical relations of landslide frequency with the physical parameters contributing to the initiation of landslides on Lantau Island in Hong Kong.

An important aspect in landslide research is the capability to store, manipulate and analyze spatial and temporal data (Dikau R., Callavin A., Jager S., 1996), and it can be done by using GIS to handle the data capture, input, manipulation, transformation, visualization, combination, query, analysis, modeling and output the landslide data. Saha *et al,* 2002 concluded that GIS-based methodologies are suitable for the development of landslide hazard maps. This research sought to develop a spatial model to identify areas of high hazard of landslide occurrence and the contributing factors using remote sensing and GIS-based data. In landslide hazard zonation using GIS, this take two predominant forms – event mapping (in this case landslide event) and distributed parameter model (terrain parameter) which are used in conjunction of each other (Hansen et al, 1995). Wang (2005) used GIS-based landslide hazard assessment. The methods consist of framework, DEM, modeling and concludes of an integrated system for effective landslide hazard assessment

The application of distributed probabilistic models is particularly suited in raster GIS. Here the individual variables considered to be significant in controlling slope stability (e.g. soil, slope, aspect, land cover) are mapped over the landscape as either discrete (e.g. land use) or continuous (e.g. slope) data (Hansen et al, 1995). The operation of each formula in raster-based GIS, the analysis can be calculated pixel by pixel. Each pixel can be treated as a homogenous area within one or more attributes, and this attributes are the input parameters necessary for model calculations. In combining data to assess landslides, a number of GIS techniques can be used such as simple overlay, sieve mapping, algebraic combination and statistical overlay (Wang and Unwin 1992 in Hansen *et al*, 1995).

Van Beek (2000) used GIS as the main tools to landslide hazard within deterministic modeling. The model was run in PC Raster® environment. Deterministic landslide hazard analysis was performs in a dynamic modeling. Van Beek (2000) was built a script of STARWARS and PROBSTAB. Those are coupled model to assess slope instability. The result was slope stability maps and failure probability maps. Sekhar (2006) use STARWARS and PROBSTAB to assess slope instability and failure probability. He was assessing the role of vegetation on debris initial flow in PC Raster® environment.

The infinite slope stability model has been widely used in landslide zonation in small areas (Terlien *et al.*, 1995; van Westen *et al.*, 1997). Vannaker (2002) describes the GIS methods used to determine the controlling factors of slope failure. He was developed the GIS method to build upon the results of the statistical analysis a process-based slope stability model. The models was included a dynamic soil wetness index using a simple subsurface flow model.

1.4.3 Hydrological Modeling

The occurrence of Sigebang landslide may be correlated with the hydrological condition of the slope. For most of the sloping area, the information of phreatic levels is hard to obtain. With limited equipment, it is difficult to assess the phreatic level information. Due to this condition, simulation of groundwater information is used to define the groundwater information. Hydrological modeling using PC Raster will be carried out. This model is trying to calculate water from the rainfall infiltrates the soil and through percolation will form groundwater. Using this model we can get information of the groundwater level. In order to run this model, information such as soil map, rainfall data, land use and meteorological data are needed. From this data we can define the amount of water which formed into interception storage, evaporation and percolation. Based from the percolation information we can calculate the groundwater flow and produce the groundwater map. Using this information and combine with the stochastic parameters (bulk density, friction angle and cohesion) we can derive a slope stability modeling using the Factor of Safety equation. PC Raster allows us to run the model, calculate a complicated function and produce a slope stability map. GIS is known as a powerful tool to combine the hydrological and slope stability modeling. PC Raster environment is used to combine those 2 models. The conceptual equations for this modeling are:

Unsaturated percolation to the ground water is assumed to take place by gravity according to the following equation, (Van Asch and Alkema, 2007):

$$Pr=Ks((\theta - \theta_s) / (\theta_s - \theta_r))a \quad (1)$$

with

Pr = Percolating flux (cm /day)
Ks = Saturated hydraulic conductivity (cm/day)
θ = Actual volumetric soil moisture content (cm3/cm3)
θr = residual volumetric moisture content (cm3/cm3)
θs = saturated volumetric moisture content (cm3/cm3)
a = constant (between 3 and 8)

The groundwater flows define according to the Ldd direction imposed by the topographical relief. The topographical relief is the result of the DEM computation. Ground water flow is calculated according to the following function, (Van Asch and Alkema, 2007):

$$Q=K_s z_w B \sin \beta \quad (2)$$

Q =ground water flow in cm3 per timestep
Ks =Saturated hydraulic conductivity
zw =height of the ground water table (cm)
B =width of flow (=width of pixel) (cm)
Sin β =sinus of the topographical slope (-)

1.4.4 Slope Stability for Landslide Hazard Zonation

Landslides usually occur in hilly or mountainous areas which is having low slope stability. Slope stability can be influence by many variables such as climate factors and terrain factors. A quantitative assessment of the slope stability was very important in landslide hazard

assessment. The point of this assessment was to determine whether the slope is stable or not. There are numbers of different method of slope stability assessments that available, but they were broadly similar in concept. In the slope stability analysis, the level of slope stability is expressed in factor of safety. Factor of safety defined by:

$$F = \frac{Sd}{Sc}$$ (Anderson and Richard, 1987) ..... (3)

Where F : factor of safety,
Sd : Shear strength available,
Sc : Shear strength required for stability.

The slope might failure if F=1. At this condition, the slope is critical. When the F<1, the slope suppose already fail. The slope is stabile if F>1.

Several methodologies are developed to assess the slope stability (table 1.2),(Nash, 1986). To select the appropriate method, was based on the interslice forces that work on the slope.

Table 2 Method for slope stability analysis

Method	circular	Non - circular	Overall movement equilibrium	Overall force equilibrium	Assumptions about interslice forces
Infinite slope		*		*	Parallel to slope
Qu=0	*		*		
Ordinary	*		*		Result parallel to base of each slice
Bishop	*	(*)	*		Horizontal
Janbu simplified	(*)	*		*	Horizontal
Lowe & Karafiah	*	(*)		*	Define inclination
Spencer	*	(*)		*	Constant inclination
Morgenstein & Price	*	*	*	*	XE =λ. F(x)
Janbu rigorous	*	*	*	*	Define thrust line
Frelund &Krahn GLE	*	*	*	*	X/E =λ. F(x)

Note: E and λ are horizontal and vertical components of interslice force respectively. (Nash, 1986)

Infinite slope analysis is one of the methods to assess the slope stability. This method was assumed that the soil slides on a slip surface which is approximately parallel to the ground surface (Skempton and Delory, 1957 in Nash, 1986) and the slope was assumed to be infinite in extent at an inclination β to the horizontal (Nash,1986)

The stability model was tried to calculate the slope stability in terms of a Safety Factor. The Safety Factor is the ratio between the available shear strength to the shear stress. The infinite slope model was used to calculate the stability. In this model it was assumed that the slip surface of the landslide was running parallel to the topographical slope. In that case the stability can be calculated for each pixel.

The safety factor is given as, (Van Asch and Alkema, 2007)::

$$\mathbf{F= (c'+(\gamma z\cos^2\beta-u)\tan\Phi')/(\gamma z\sin\beta\cos\beta)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

With
F = Factor of safety (-)
c' = Soil cohesion (kN/m2)
γ = Unit weight of soil kN/m3)
z = Depth of the soil (slip surface) (m)
u = Pore water pressure (kN/m2)
β = Angle of the topographical slope

The height of the water table is related to the input of rain and the subsurface drainage of ground water along the slope. It is calculated with this hydrological model. The result of the water table will be used to calculate the pore water pressure. The pore water pressure is related to the height of the ground water above the slip plane in the slope as follows. (Van Asch and Alkema, 2007):

$$\mathbf{u=\gamma_w z_w \cos^2} \beta \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

γ_w = Unit weight of water kN/m3)
z_w = Height of the water table above the slip surface (m)

1.5 Research Limitation

The objective of this research was to determine the slope stability using PC Raster simulation. To run simulation, STARWARS and PROBSTAB script from Van Beek, 2000 was used. The STARWARS was tried to model the hydrology cycle in a sloped area. Unfortunately, the fieldwork was conduct during dry season. In this condition, the information on interception storage and trough fall can not be obtained. Due to this condition, the information on the interception storage and trough fall can not be calibrated.

The groundwater data was not available in this area. Due to this condition, calibration of the water level simulated results could not be done. Therefore, the result of this model was considered as a good result. Since water level information is one of the most important inputs for the slope stability, the slope stability can be over estimated because there is no calibration on the hydrological model.

The information of landslide incidence that available in the study area was limited. Therefore, the information of landslide inventory map was obtained from interview and PGIS. Unfortunately, the peoples only remember the landslide that caused damage. They forgot the landslide which occurs as natural phenomena. In this condition, the calibration of the slope stability models can be under estimating.

The information of DEM was playing an important role in this study. The best DEM that available in the study area was only from topographic maps in scale 1:25.000 and 12,5m of contour interval. This DEM was updated by DGPS measurement and Laser survey. Due to the difficult terrain and lack of time, the updated DEM was only conducted in selected area from aerial photograph interpretation. By overlaying the contour map from topographic maps and the aerial photograph, we decide which area should be updated by DGPS measurement. The result of new DEM was 7,5m resolution. Since the updated point was relatively small, the result might give the same expression to the source (topo DEM).

1.6 Thesis Structure

The structure of the thesis consists of 8 chapters. These chapters are described as following:

a. Chapter 1
   This chapter introduces the background of the research, the problem definition, objective and the research question. In this chapter also includes the literature review and some of the previous similar research.
b. Chapter 2
   This chapter deals with the research methodology. The research was divided into 5 phase they are: 1.) preparation phase, 2.) fieldwork and data acquisition, 3.) Modeling and analysis, 4.) validation and calibration and 5.) reporting phase. Preparation phase comprise of literature review, ancillary data collection, and fieldwork preparation. Fieldwork and data acquisition comprise of spatial data collection, hydrological data, collecting soil sample, interview and "P"GIS. Modeling and analysis phase consist of building and running the models in PC Raster environment, i.e. STARWARS and PROBSTAB. Validation and calibration phase consist of validation of the model using landslide inventory map, evaluation of the model using sensitivity analysis. The landslide hazard assessment is done by generate a landslide probability map.
c. Chapter 3
   This chapter deals with explanation about the physical condition and landscape characteristic of the research area, which include geographic location, geomorphology, geology, meteorology and hydrology, land use and the information of natural hazard in the research area.
d. Chapter 4
   This chapter explains about DEM generation including topographic maps, field measurement using DGPS and Laser, collecting GCP for aerial photograph using DGPS and post processing to generate the final DEM.
e. Chapter 5
   This chapter aims to achieve the objective of the research, which is to modeled the slope stability of a sub-catchments using PC Raster simulation. At first, we modeled the hydrological condition of the research area using STARWARS to get the ground water map. The result of STARWARS model will be used to run the slope stability model using

PROBSTAB. The slope stability will be calculated using infinite slope method. Finally the result of the slope stability model is a map with safety factor value.

f. Chapter 6
   This chapter explains how to assess the landslide hazard which is done by probability curve. The curve is the slope stability vs. slope. From this landslide probability curve, we can generate the landslide probability map.
g. Chapter 7
   Chapter 7 deals with validation and evaluation of the model, both STARWARS and PROBSTAB. This chapter explains how validate the model is. Beside that, this chapter also evaluates the model, what the most sensitive parameter to the model and how accurate the model applied in the research area.
h. Chapter 8
   Present the conclusion from the research followed by recommendation.

2 Research Methodology

Landslide phenomena were related to a large variety of factors. These phenomena are involving both physical environment as well as human interaction (van Westen et al., 1993). It requires knowledge and a large of data in order to assess the landslide hazard. Table 2 shows us the data needed and how it will collect.

The methodology of this research can be classified into 5 phases, i.e. 1) literature review, ancillary data collection and fieldwork preparation, 2) fieldwork data acquisition, (data collection and handling phase), 3) hazard modeling and analyzing phase, 4) calibration, validation and evaluation phase and 5) layout and final reporting phase. Data preparation, collection and handling phase include the collection of aerial photograph and satellite images of study area, geological map, soil map, topographical map, land use map, landslide recording data and other data which relevant to this research. Fieldwork will be conducted in the study area to check the validity of each input map and to collect the soil samples both undisturbed and disturbed samples.

The next phase is the landslide hazard modeling phase. Probability modeling was applied to build the landslide hazard map. The validation of the results including here hazard map analyzing and comparing will be done in fourth phase. In this phase, the landslide inventory map from PGIS was used as the validation tool.

Evaluation of the model is to determine the advantages and limitations of the models. The last phase was layout of all maps and reporting of all activities of this research. The detailed explanation of research methodology include the data needed can be seen at the following part. The schematic visualization of research methodology represented in Figure 5.

2.1 Preparation Phase

The preparation phase comprised such as literature study, ancillary data collection, and fieldwork preparation. For the literature study was done along the research processes. This process was carried out in order to obtain the research knowledge and developed the methodology as well. The literature study most dealing with the landslide hazard, GIS modeling, specifically on PC raster, Slope Stability, and hydrological modeling. The literature study on landslide hazard included the causes of sliding, processes and their impact. GIS modeling was studied, especially to obtain the knowledge of the Hydrological – Slope stability modeling in GIS environment. The PC Raster was studied and elaborated in order to run the complicated equation and calculated into spatial information. This software provides facilities to run a dynamic modeling. Using PC Raster, ILWIS and ArcGIS/View, the spatial analysis would be done.

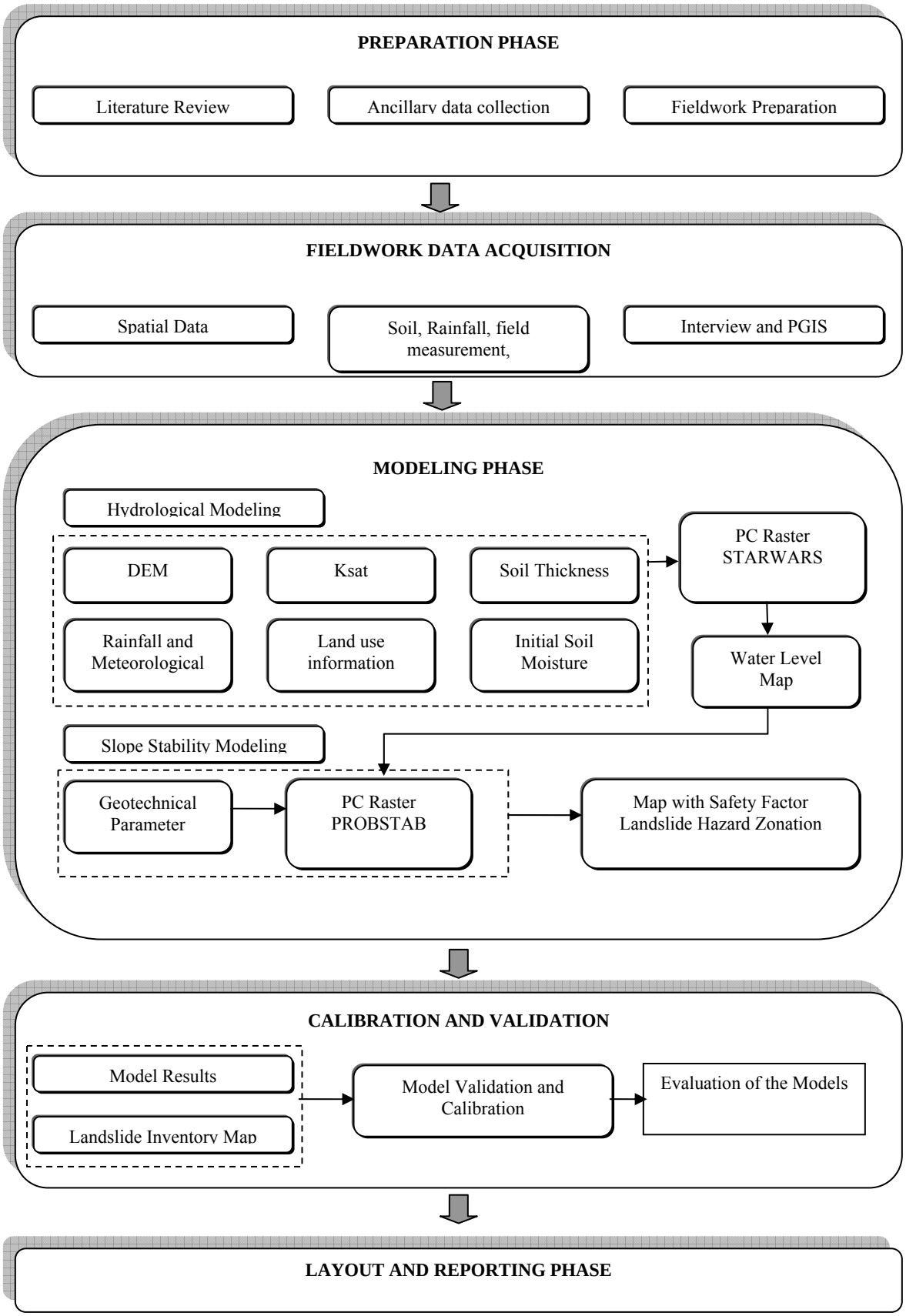

Figure 5 Research methodology

The next step in the preparation phase was ancillary data collection. Collecting reports and journals on the topic of research was done. Previous research was collected especially in the Kaligesing Sub-District area. Report of the "KKN Tematic" research (UGM, 2005), bachelor thesis report from Gadjah Mada University (such as Samsyul, 2005), report from the board of regional planning and development (Bappeda Purworejo), report from the Kaligesing Sub-District of the Hazard and Disaster information (2006), have been studied. Those and other reports and journals are used as reference for this study and for writing of chapter 3 (Physical Environment and Landscape characteristic). In additional, valuable information was obtained from interview and consultations. The last step on the preparation phase was fieldwork preparation. This step includes collecting soil sample, obtaining research permit from local government, and preparation the equipment for measurement

2.2 Fieldwork and data acquisition

This phase comprised the fieldwork and data acquisition activities. In this phase, spatial, hydrological, climatological and meteorological data was collected from several offices in the research area. Field observation and investigation was done in this phase. The activities in this phase including collecting soil parameters, DGPS measurement, Interview and PGIS (Participatory geographic information system). The detailed data needed for this research, as well as the method how it was obtained shown in Table 3.

The activities that included in this phase are:

1. image interpretation,
2. Soil sample collection,
3. Interview,
4. PGIS,
5. Downloading rainfall data,

Image interpretation in this research was done using Aerial Photo in the scale of 1:20.000 year 1993 from PERHUTANI and year 2001 from Merapi Project. Aerial photograph interpretation was done by visual interpretation. This step was done in order to get the detail geomorphologic features of research area, landform classification based on their origin including here the geomorphologic process, lineament and geological structure identification, and land use mapping. During this phase, ground control point (GCP) was collected. The GCP was used to do DGPS measurement. Using DGPS measurement we can update Topo DEM into ne DEM in 7, 5 m resolution.

Table 3 Overview of input data needed (van Westen, 1993)

No	Data Type	Method and Sources of Data	Tools
1	Geomorphology		
	a. Geomorphology units	Geomorphology map, Image interpretation Aerial Photograph and field check	ILWIS, Arc GIS
	b. Landslide data	PGIS, Field investigation and field measurement	DGPS, Ancillary data
2	Topography		
	a. Digital Elevation Model (DEM)	Generate from TOPO Map, Aerial Photograph and DGPS Measurement	DGPS, ILWIS
	b. Slope Map	Generate from DEM	ILWIS
	c. Slope direction map	Generate from DEM	ILWIS
3	Engineering Geology		
	a. Lithology	From geological map and field check	Geological Map
	b. Structure	From geological map and field check	Geological Map, Geological Survey
4	Land use		
	a. Land use map	PGIS, field check and field description	Arc GIS, ILWIS
	b. Damage information	Administration map (village), field check, interview and field description	Questionnaire,
5	Soil		
	a. Soil Properties	Field investigation	Soil Test Kit, Munsel Color Chart, ITC Ganfeld
	b. Soil moisture	Field investigation	Soil Test Kit
	c. Soil thickness	Field investigation	Laser Ace, Tape Measurement, DGPS
	d. Stochastic parameters (bulk density, friction angle, cohesion)	Field and laboratory investigation	Soil Sampler (for undisturbed soil sample)
6	Hydrology		
	a. Drainage	Generate from DEM using LDD-PC raster	PC-Raster
	b. Catchments area	Topographic map or modeling from DEM	ILWIS
	c. Meteorological stations	Collection of existing meteorology data	Rain Gauge
	d. Water table	Field measurement of K-sat and modeling	Hydrological Model

Soil investigations are an important phase in this research. The result of this result was used to run the model. In this soil survey, several investigations were carried out such as the collecting of soil samples both disturbed and undisturbed soil samples and soil depth investigation. Soil samples were analyzed in the laboratory to get information about Ksat, bulk density, porosity, textures, and geotechnical parameters. In order to get a good result, a design of soil samples was made. The sampling area has a crucial point in this study. Stratified random sampling was carried out in order to make a sample design sample. Regarding the land use condition, 12 soil samples were collected to get Ksat information. There were 3 types of land use and in each type of land use, 4 soil samples has been collected. From this sample, bulk density investigation was done. 12 undisturbed soil samples have been collected to get the geotechnical parameters. These samples were analyzed in the laboratory using two different methods. They are *direct shear* and *Triaxial test.* The result of this investigation was used to calculate the slope stability in the form of *safety factor*. Figure 7 revealed the design sample for geotechnical sample.

Soil depth was one of important parameters to run the slope stability model. This information was obtained by field investigation. To measure the soil depth, tape measurement, Terrestrial laser scanning and DGPS were used. If the profile was visible and easy to reach, the tape measurement was used. But if the profile is hard to reach, laser survey was applied. Random sampling has been used to collect samples for soil depth. The sampling was take place along the roads, valleys, gully erosions, and other outcropped slope. These locations were selected with several assumptions. For the roads, we assume that road cuts are needed along the sloping areas. To get the stable road, they have to reach the bedrock. In this condition, the soil depth will be measured. Figure 6 revealed the soil depth measurements along the roads. The second location is in incised valleys or gullies. The assumption is that these are reaching the bedrock. In this condition, the soil depth was measured.

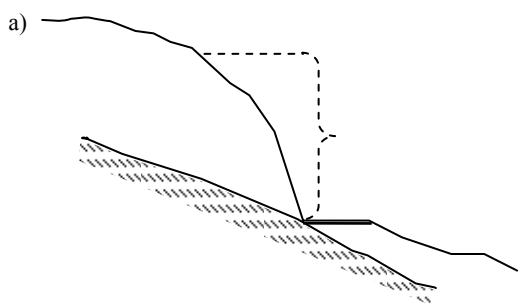

Figure 6 Soil depth measurements along the roads

The information on the occurrence of past-landslides sometimes was difficult to obtain if the hazard data base is not well updated. In order to get that information, an interview method has been carried out. Open interviews were used to get in depth information without using a questionnaire. To get a good in formation, we stratified the respondents. The first levels of respondents were the heads of the village with assumption that they know well their area. The second assumption, all the incident of landslide was reported to the village office, in this case the information will reported to the head of the village. The other respondents were the staff of the village office especially the secretary of the village with assumption that he has the report of landslide incident. The next level of respondents was the villagers near by the landslide area.

PGIS was one of powerful method to obtain unrecorded information. From this activity, we can get the location of the landslide in the map. The activity of PGIS also produces a tentative land use map. The map was consisting of the location of houses, the type of vegetation cover, road, rivers and the landslide point. The respondent for the PGIS are the head of the village and staff, the secretary of the village, the imam, head of the sub-village, and some villagers. The location of PGIS was take place in the Purbowono village office. The local language, Java, was used in this process.

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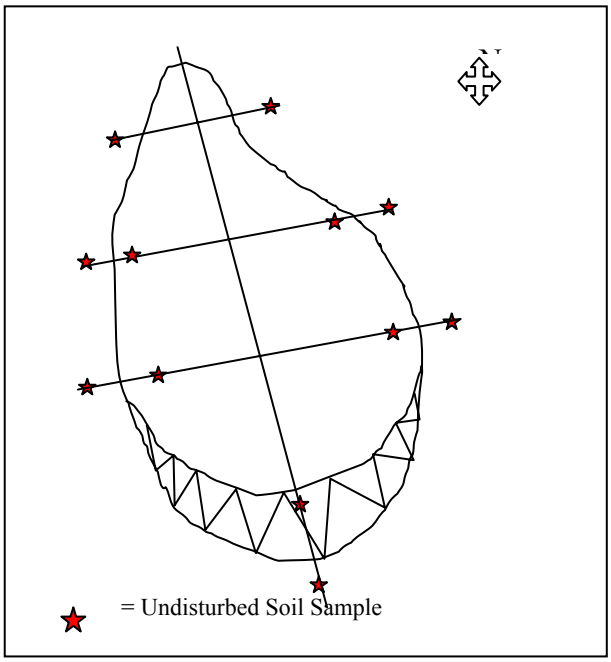


Figure 7 Sample design for collecting soil samples (undisturbed)

2.3 Modeling and Analysis

This chapter consists of running the two models, i.e. hydrological model and slope stability model. The main input for the hydrological model was DEM, soil properties, land use information and hydrological data (climate and meteorological data). The model will run in GIS environment using PC Raster software. This software is GIS software that provides computation from a dynamic input.

The model chosen for this research was STARWARS and PROBSTAB (Van Beek 2002 and Sekhar 2006)). Those are physical based dynamic models. Those were coupled model and very data demanding. Shekar, 2006, said that this model has several additional advantages such as:

1. Tight coupling of distributed, physically based hydrological and slope stability model in GIS environment (PC Raster®);
2. Dynamic in order to simulate transient hydrological triggers;
3. Applicable to all cases in which percolation stagnates on less permeable layers;
4. Adaptable to various data availability condition.

Figure 8 shows the schematic of STARWARS and PROBSTAB for slope stability modeling. The output from the STARWARS modeling (hydrological modeling) was used as an input for

the PROBSTAB modeling (Slope stability modeling). Table 4 shows the data needed for each model and the expected output.

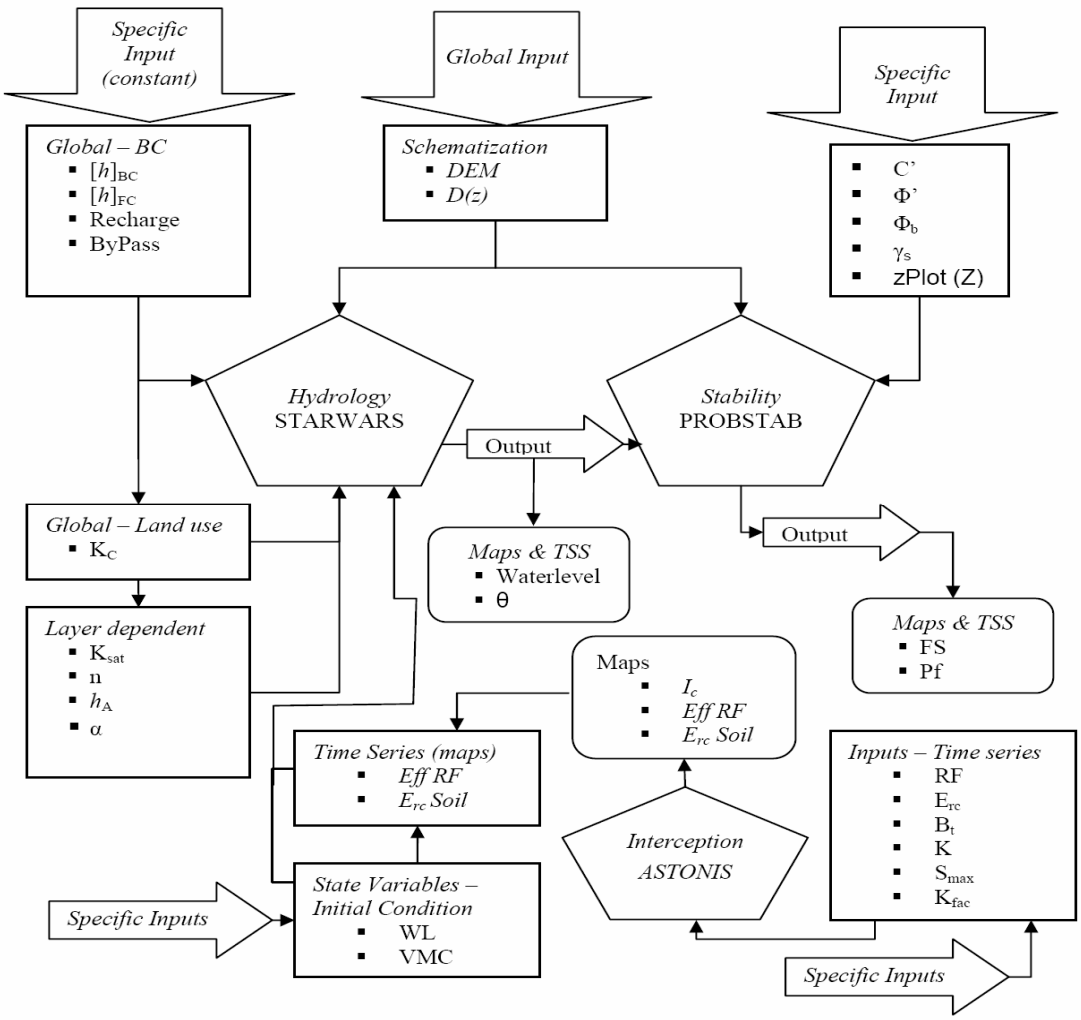


Figure 8 Flow chart of the Hydrological – Slope Stability Modeling using PC Raster (Van Beek, 2002 and sekhar, 2006)

2.3.1 Hydrological Modeling

STARWARS simulates the spatial and temporal dynamics of moisture content and perched water levels in response to gross rainfall and evapotranspiration (sekhar, 2006). In reality, before reach the ground, the rainfall was reduced by interception storage. Normally, the result from interseption storage will produce a steam flow. In the model, this information was avoided because of the difficulties and time consuming.

The soil profile was subdivided into tree layers. This condition allows variations in the soil properties with depth and perched water can move freely within soil column. In the model, infiltration was added in the upper most unsaturated layer. Percolation trough unsaturated layers was calculated based on gravitation unsaturated flows only. To facilitate the expressed as water slice and the conversion from volumetric moisture content to the effective degree of saturation was calculated as follow:

$$\theta_E = \frac{\theta - \theta_{res}}{\theta_{sat} - \theta_{res}} \quad \text{.....} \quad (6)$$

Where,

Θ_E = Volumetris moisture content
Θ_{sat} = the saturated moisture content which is set to porosity
Θ_{res} = residual moisture content

Table 4 Model input and output for STARWARS and PROBSTAB

Model component	**ASTONiS**	**Hydrology - STARWARS**	**Stability - PROBSTAB**
		Model Input	
Constant parameter value	▪ Fraction vegetation cover (K_{fac}) ▪ Maximum Canopy Storage S_{max} *(mm)* ▪ Correction factor *k(-)*	*Global boundary condition* ▪ Matric suction for lower boundary $[h]_{BC}$ *(m)* ▪ Matric suction at field capacity, 1st layer $[h]_{FC}$ *(m)* *Global land use dependent* ▪ Crop factor k_c *(-)* *Layer dependent* ▪ Saturated hydraulic conductivity k_{sat} $(m.d^{-1})$ ▪ Porosity *n* $(m^3.\ m^{-3})$ ▪ Air entry value h_A *(m)* ▪ SWRC slope *α (-)*	*Layer Dependent* ▪ Cohesion *C (kPa)* ▪ Angle of Internal Friction Φ $(^0)$ ▪ Dry bulk density of soil γ_s $(kN.m^{-3})$
Dynamic Input – All timestep	▪ Reference potential evapotranspiration E_{rc} $(mm.d^{-1})$ ▪ Rainfall *RF* $(mm.d^{-1})$	▪ Effective rainfall *Eff RF* $(m.d^{-1})$ ▪ Remnant of Evapotranspiration to occur from soil E_{rc} *Soil* $(m.d^{-1})$	▪ Effective degree of saturation *(-)* ▪ Groundwater level *WL (m)*
Initial condition – state variables	▪ Interception I_c *(m)* ▪ Effective Rainfall *Eff RF* $(m.d^{-1})$ ▪ Remnant of Evapotranspiration to occur from soil E_{rc} *Soil* $(m.d^{-1})$	▪ Groundwater level *WL (m)* ▪ Volumetric Soil Moisture Content *VMC* $(m^3.\ m^{-3})$	▪ Factor of Safety *F (-) (set to 999, indicating stable initial conditions)*

Model component	ASTONiS	Hydrology - STARWARS	Stability - PROBSTAB
Model Output			
Maps and timeseries	▪ Interception I_c *(m)* ▪ Effective Rainfall *Eff RF* ($m.d^{-1}$) ▪ Remnant of Evapotranspiration to occur from soil E_{rc} *Soil* ($m.d^{-1}$)	▪ Groundwater level *WL (m)* ▪ Volumetric Soil Moisture Content *VMC* ($m^3 . m^{-3}$)	▪ Factor of Safety *F (-)* ▪ Probability of failure P_f *(-)*

(Based on: van Beek 2002 and sekhar 2006)

2.3.2 Slope Stability Modeling

The second modeling was slope stability modeling. This model was tried to calculate the slope stability using infinite slope methods. This model was calculating the slope stability pixel by pixel. In this manner, GIS environment was used. PC Raster was used to run the dynamic processes. In order to run the dynamic process, the script of PROBSTAB (modified) was used. The result of this model was Slope stability map and probability of landslide. Based from this information, the landslide hazard map was produced.

Probabilistic landslide hazard modeling was creates quantitative hazard maps. The hazard degree can be expressed by the sa*fety factor (fs)*, which is the ratio between the forces that make the slope fail and those that prevent the slope from failing. Many different models exist for the calculation of Safety Factors. In this research will use *infinite slope model*. This two dimensional model describes the slope stability of slopes with an infinitely large failure plane. It can be used in a GIS, as the calculation can be done on a pixel basis. The pixels in the parameter maps can be considered as homogeneous units. The effect of the neighbouring pixels is not considered, and the model can be used to calculate the stability of each individual pixel, resulting in a hazard map of safety factors. The safety factor is calculated according the following formula (Graham, 1984):

$$Fs = \frac{c' + (\gamma - m\gamma_w) z \cos^2 \beta \tan \phi'}{\gamma z \sin \beta \cos \beta} \quad \text{.....} \quad (7)$$

Where:

c' = effective cohesion (Pa= N/m^2).

γ = unit weight of soil (N/m^3).

m = z_w/z (dimensionless).

γ_w = unit weight of water (N/m^3).

z = Depth of failure surface below the surface (m).

z_w = Height of water table above failure surface (m).

β = slope surface inclination (°).

φ' = effective angle of shearing resistance (°).

The classification of the landslide hazard was based on the value of the safety factor. The higher safety factor (fs) will produce the higher slope stability so the hazard level is lower. The hazard level can be classified in Table 5.

Table 5 Slope stability classification

No	Fs Value	Slope stability	Hazard Level
1	Fs > 1,5	High stable	Low hazard
2	1,00 ≤ Fs ≤ 1,5	critical slope	Medium hazard
3	Fs < 1,00	unstable slope	High hazard

(Sources: Hadmoko, 2004)

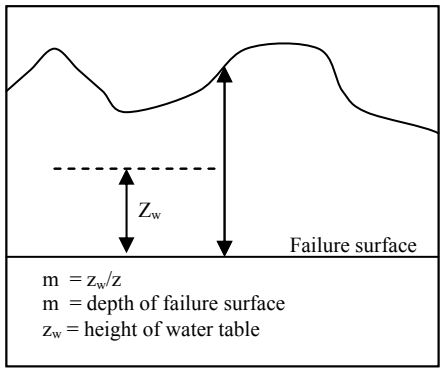


Figure 9 The schematic view of the failure surface and groundwater level (Hadmoko, 2004).

2.4 Validation and Calibration

This phase was dealing with the validation, evaluation and calibration of the models. For the validation, cross maps between the models results and the landslide inventory maps was done.

Evaluations of the models have been done by analyzing and evaluating the input parameters, process and the models results. The analytical approach was used to determine the advantages and the limitations of the models and the software. Sensitivity analysis was done to find out the most sensitive parameters for the slope stability modeling.

For validation of the model results, cross maps between model results and reliable source maps was calculated. The accuracy and reliability values are used to validate the model. In this case, accuracy is the fraction of correctly classified reliable source map (or as a ground truth) pixels of a certain reliable source class of landslide hazard level.

In this research, the statistical analysis will be used to test significance validation of landslide hazard map. Each scenario landslide hazard map was tested using landslide inventory map from PGIS process to get the most suitable model to real condition. To test the validity of output map, will be used the mathematical equation presented by Yin and Yan, 1988 in van Westen, 1993:

$$A = \frac{Mi}{Ni}\sqrt[3]{\left(1 - \frac{M - M_i}{N - Ni}\right)} \quad \text{.....} \quad (8)$$

Where,

A = precision of the predicted result
N = total number of terrain unit in the study area
N_i = number terrain unit with landslides
M = number of terrain unit predicted as unstable
M_i = number of terrain units predicted as unstable which landslides

2.5 Reporting Phase

The final result of the research was translated in to conclusion and recommendation. This phase was very important because by the research report, we can communicate the result of the research with others in order to get a good feedback.

3 Physical Environment and Landscape Characteristic of the Study Area

3.1 Geographic Location

The study area is located on the Probolo Catchments of Gesing Sub-District, Purworejo, Indonesia. Almost 80% of the Probolo Catchments is located at Purbowono Village, part of Gesing Sub-District. Probolo sub-catchments are located in the upper part of Bogowonto watershed. . Figure 10 shows us the location Probolo sub-catchments. The highest point in the study area is 751m msl and 415m msl as the lowest point.

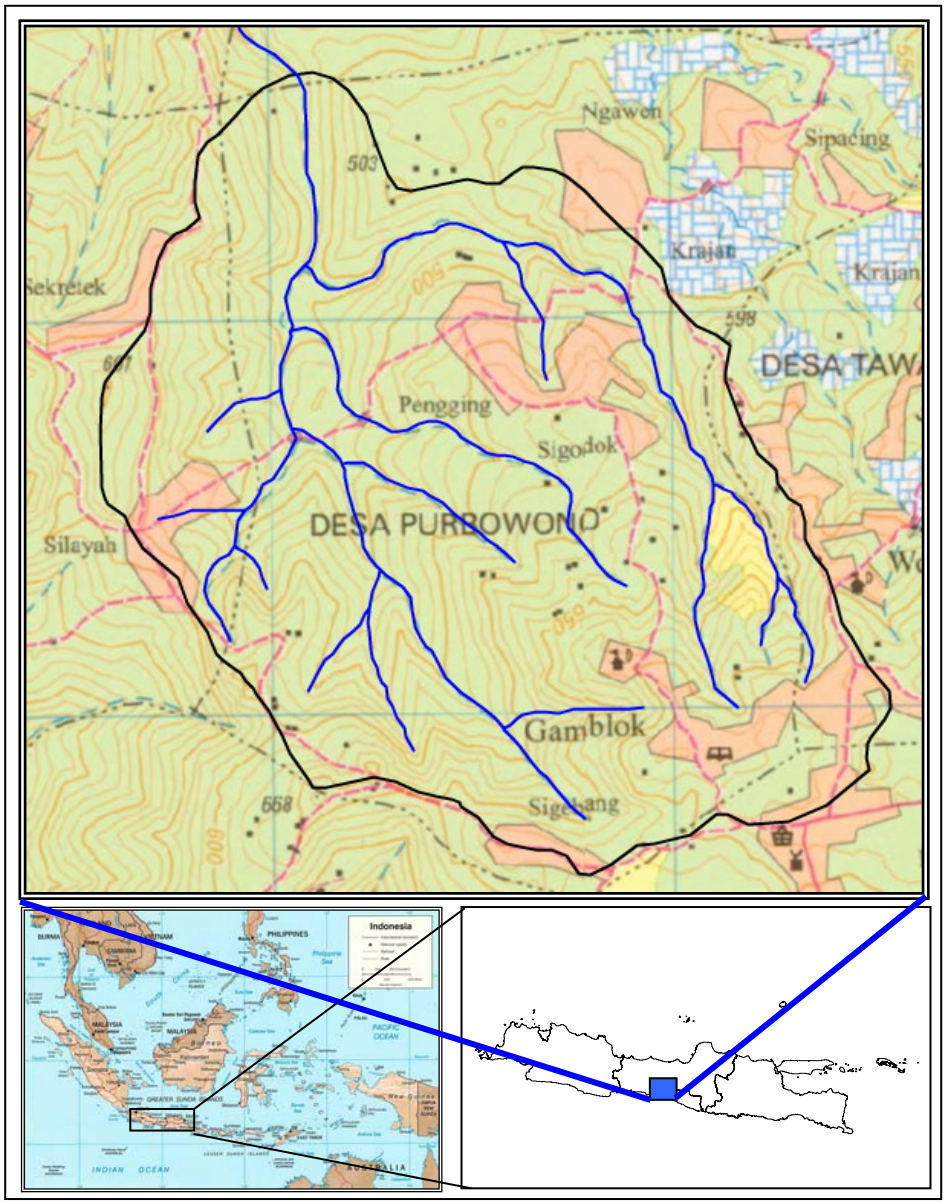


Figure 10 Research area

3.2 Geomorphology

The geomorphology of the research area can be classified roughly into structural landform, part of the structural mountain of Menoreh. The detailed geomorphology condition of the research area was derived from aerial photo interpretation scale 1:20.000 of year 1993 and 2001. Based on the aerial photo interpretation, there are 3 detailed calcification of landform of the research area. There are:

1. Upper slope of structural hills
2. Middle slope of structural hills
3. Lower Slope of structural hills

The geomorphologies of the research area mainly influence by the structural processes which is one the major process in the Mount Menoreh area after volcanic process. The volcanic process it self mainly influence on the material of the research area. The major landform of the research area was structural hills, part of Menoreh Mont. Since the major landform was structural, the material was weathered by climates and the slope was steep to very steep, the mass movement processes was become one of the major process that build the research area.

3.3 Geology

In general, the research area was located at Old Andesite Formation or formation of van Bemmelen of Menoreh Mount. This formation was formed during Oligocene up to first Meiocene. This formation consists of andesitic breccias, tuff, and lappily tuff, and andicitist lava flow. Lava that formed in this research area was mainly Andesit hiperstein and Andesit-Augit-Hornblenda. In this formation, the weathered andesitic breccia was very thick. The weathering process in this research area generally is a mechanic weathering which is formed a brownies soil in the upper layer. Figure 11 revealed the geological setting of research area and it's surrounding.

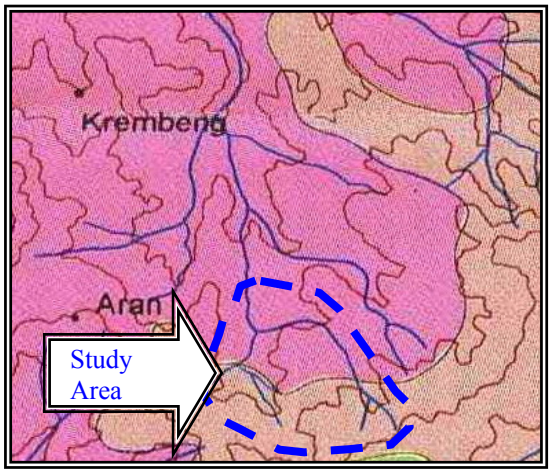


Figure 11 Geology condition of the study area

3.4 Meteorology and Hydrology

In general, the research area is located in the tropics with high rainfall intensity. From the rain gauge near by the research area, we found that the rainfall intensity of this area is around 2600 mm/year. The maximum intensity of the research area was happened in the year 2006. Around 4000 mm/year was recorded in this area. Figure 12 shows the total yearly rainfall from 1990 up to 2006. As we can see in the Table 6, we can understand that the rainfall intensity in the research area was relatively high.

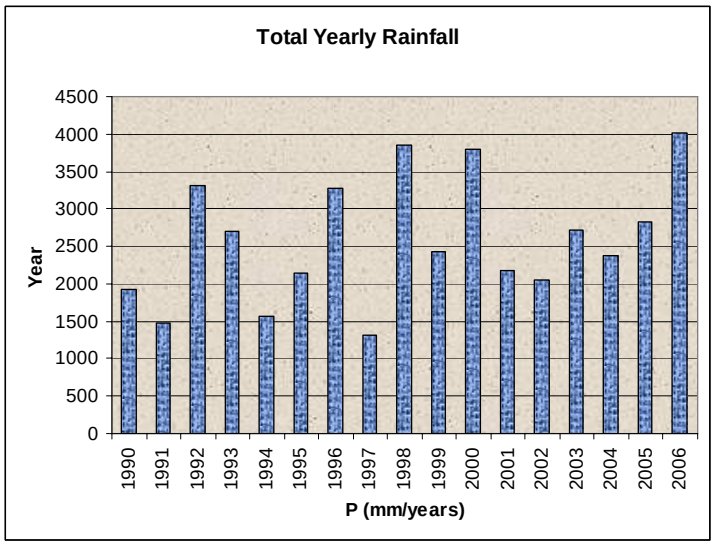


Figure 12 Total Yearly rainfalls

Based on the rainfall intensity, Indonesian seasons can be divided into 2 seasons i.e., dry season and wet season. Figure 13 revealed the average monthly rainfall intensity. The dry season usually started from Mei up to October. And the wet season started from November up to April.

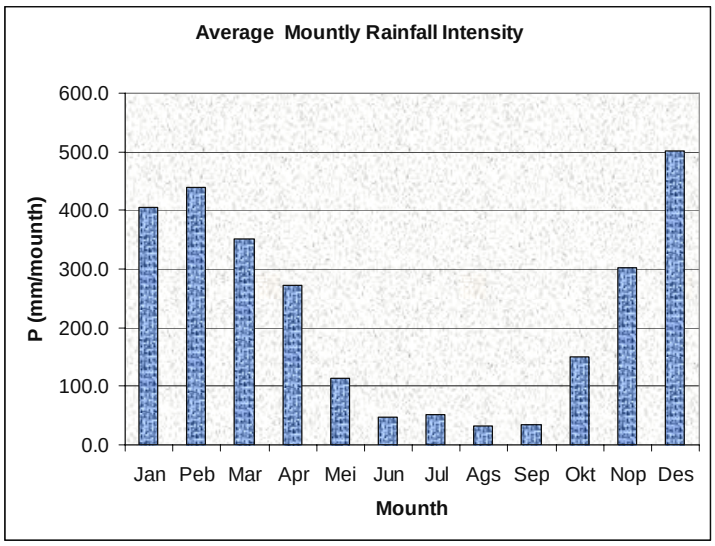


Figure 13 Average monthly rainfalls

Table 6 Monthly rainfalls in the Probolo Sub-Catchments

Year	Month												Yearly
	Jan	**Feb**	**Mar**	**Apr**	**Mei**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Des**	**Sum (mm/thn)**
1990	307	193	268	114	106	81	239	52	83	0	0	487	1930
1991	449	430	166	134	0	0	0	0	0	0	134	159	1472
1992	238	307	171	513	89	-	0	261	342	291	812	289	-
1993	602	298	355	436	65	71	0	0	0	0	326	545	2698
1994	322	381	485	233	35	0	0	0	0	0	84	35	1575
1995	304	295	-	75	23	0	23	105	29	360	446	487	-
1996	353	847	532	75	23	0	23	105	29	360	446	487	3280
1997	415	444	85	138	48	0	0	0	0	0	26	151	1307
1998	146	427	515	686	7	507	248	19	38	483	383	396	3855
1999	633	247	355	233	206	0	0	0	0	57	366	325	2422
2000	177	536	554	296	244	0	0	9	52	441	918	574	3801
2001	623	391	531	536	132	64	145	0	0	300	85	-	-
2002	-	988	189	60	0	0	0	0	0	0	265	558	-
2003	350	593	305	60	116	0	0	0	18	180	311	785	2718
2004	549	165	396	0	549	9	140	0	0	0	266	311	2385
2005	466	565	350	344	0	17	57	0	0	79	286	668	2832
2006	553	352	356	707	294	0	0	0	0	0	0	1756	4018
Max	**633.0**	**988.0**	**554.0**	**707.0**	**549.0**	**507.0**	**248.0**	**261.0**	**342.0**	**483.0**	**918.0**	**1756.0**	**4018.0**
Avg	**405.4**	**438.8**	**350.8**	**272.9**	**113.9**	**46.8**	**51.5**	**32.4**	**34.8**	**150.1**	**303.2**	**500.8**	**2637.9**
Min	**146.0**	**165.0**	**85.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**35.0**	**1307.0**

Source: BPDAS Probolo

3.5 Land use

Land use is an important factor that may trigger the landslide in this area. From the aerial photograph interpretation of 2001 at scale of 1:20.000, PGIS and the administration map of Purbowono village, the land use map was produced. From the image interpretation, it is known that the most land used types are vegetation and settlements. This information of land use will be used as an input for the hydrological – slope stability model. In this manner, we divide the land use type into 3 major types. There are:

a. Type 1, built up area (settlements)
b. Type 2, Secondary vegetation,
c. Type 3, Primary vegetation,

Figure 14 Land use type 3 (Primary vegetation)

In general, the land use of the research area was typically people forest. Figure 14 shows the land use type 3 which is consist of primary vegetation i.e. cloves, coco tree, and other tall tree. Since the land used of the research area was typically people forest, primary was dominant in the research area. Figure 15 revealed to land used type 2. They consist of grass, banana, shrub and others short tree and plantation such as *mahkota dewa* (traditional herbs, known as crown of the God's) and cassava.

Figure 15 Land use type 2
Secondary vegetation such as banana, elephant grass and cassava.

3.6 Natural Hazard

The information of natural hazard in the Purbowono Sub-District shows that the most intense hazard in this area is mass movement. At least 15 devastating landslides were recorded as hazard since 1990. Figure 16 revealed to landslide hazard inventory maps from PGIS and filed survey and measurement. The others landslides were categorized into natural phenomena. Every year during rainy season, several incidence of landslide happen in this location. Using participatory GIS and landslide information in the Purbowono Sub-District, we generate the landslide inventory map. The following landslide damages during the last landslide were confirmed by Purbowono Sub-District office (2006):

1. Death : 1
2. Injured : 4
3. House Collapse : 2
4. Building Damage : 1
5. Livestock damage : 2

This landslide happened in December 2005. In the same years, several other landslides happened, but they consider as natural phenomena and didn't cause major damage. Figure 17 shows the body of Sigebang landslide which is happens in December 2005.

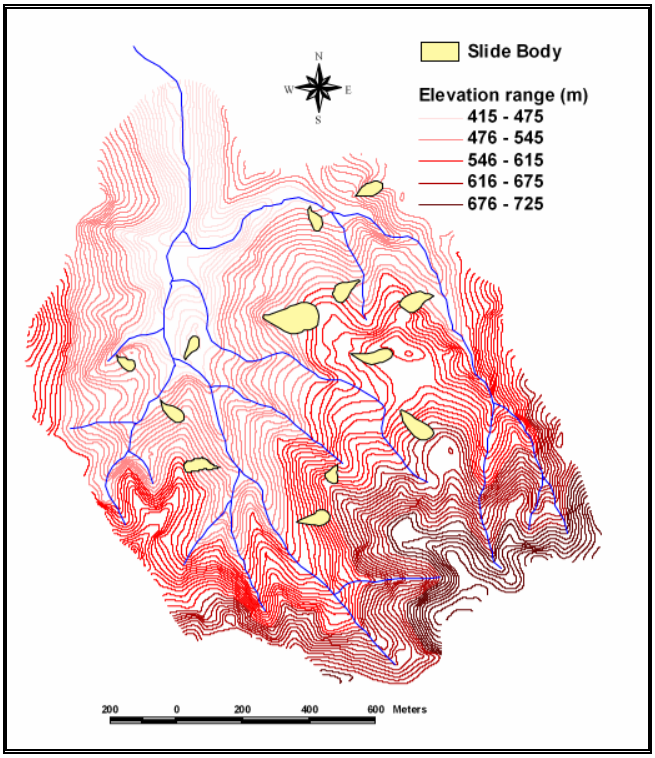


Figure 16 Landslide inventory map

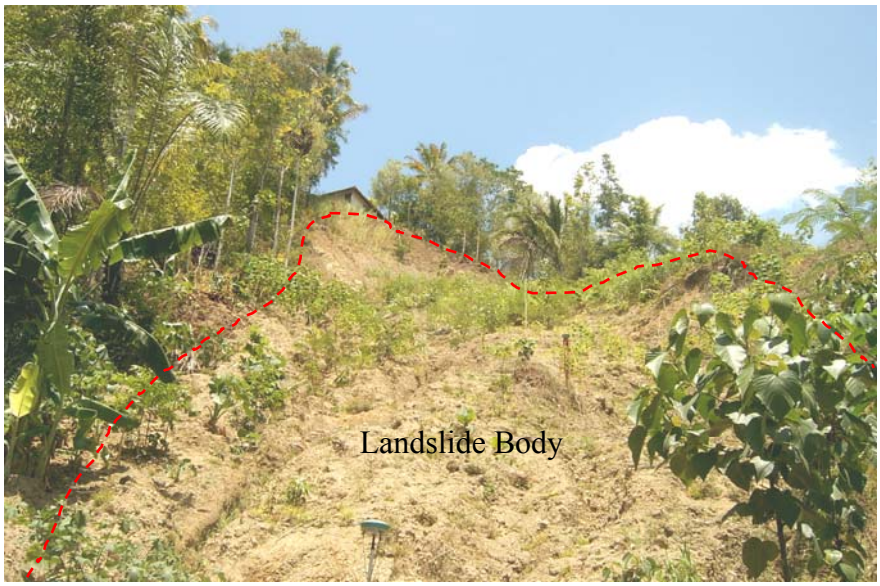


Figure 17 Sigebang Landslide

3.7 Concluding Remarks

This chapter describes the physical and landscape condition of the Probolo Sub-Catchments, the research area for the Hydrological – Slope Stability Modeling for Landslide Hazard Zonation. The description include: geographical location, geomorphology, geology, meteorology and climatology, landuse, and natural hazard in the research area.

The topography of the Probolo Sub-Catchments which is steep to very steep was triggered mass movement. The lowest elevation in the research area was 415m from means sea level and the highest was 751m from means sea levels. This process has become one of the major processes that formed the landscape of this area. Year by year the population in this area was increased. This condition create the natural processes in the form of mass movement becomes hazards.

The research area was generally located in the Andesitist Formation or Van Bemmelen Formation. This formation consist of tuff, tuff lappily, breccias andesitist, and lava flow in the lower part of the formation. The geomorphology of the research can be roughly classified into structural hills, part or Menoreh Month. The detailed geomorphology map was produce from aerial photograph interpretation. The result was shows that there were 3 types of geomorphology. They are upper slope, mid slope and lower slope of structural hills.

Meteorological condition shows that the minimum temperature in the research area was 22.7^0 and the maximum was 29.2^0. From 10 years recorded, we find out that the maximum rainfall intensity was happen in the year 2006 with 4018mm/year rainfall intensity. The minimum rainfall intensity was 1307mm/year intensity in year 1997. The average monthly rainfall shows that the study area has two types of season i.e. dry season and wet season.

Typical natural hazard in Probolo sub-catchments was landslides. These landslides occur due to the steep topography, high rainfall intensity and the geology setting of this area. From 1990 at lease 15 landslides hazard were recorded. The last landslide was Sigebang landslide. It is happen in December 2005.

4 DEM Generation

4.1 DEM Generation

A digital elevation model was generated from the 1:25.000 Topographic map of Purworejo, 1:20.000 Aerial photographs from MERAPI Project and DGPS measurement. The topographic map is used to determine the elevation point. Yet, it's still rough information since the scale was 1:25.000. This information was detailed by stereographic interpretation of 1:20.000 aerial photographs from PERHUTANI (Indonesian Forestry Company) to obtain ground control point. DGPS measurement and terrestrial laser survey was carried out to generate the new DEM. Point interpolation was used to produce new DEM with 7,5m resolution. To produce a DEM map in raster from the point map, ILWIS Software is used.

This DEM format will be used for: (1) three-dimensional view of the study area in different direction, (2) as an input parameter for groundwater simulation in hydrological modeling, (3) as an input for slope stability modeling. To perform the DEM generation, several steps were done, i.e.:

1. Generate DEM from contour of the Topographic map (10m resolution)
2. GCP selection from aerial photo interpretation.
3. Differential GPS point collection using Trimble DGPS and Sokkia DGPS and laser survey
4. Post Processing of point data using
5. Generation DEM with 7,5m resolution using Ilwis 3.4

The topo DEM was generated from topographic map of Purworejo form BAKOSURTANAL (Indonesian Mapping Agency). To produce a Topo DEM, contour line (Figure 18) were interpolated using ILWIS 3.4. First, the Information of contour lines imported into ILWIS and contour interpolation was carried out in order to determine the Topo DEM. This process was done in 5 by 5m pixel resolution. Several methods were used to get the best DEM. Moving average and kriging interpolation was compared. The result was a Topo DEM with 10m resolution.

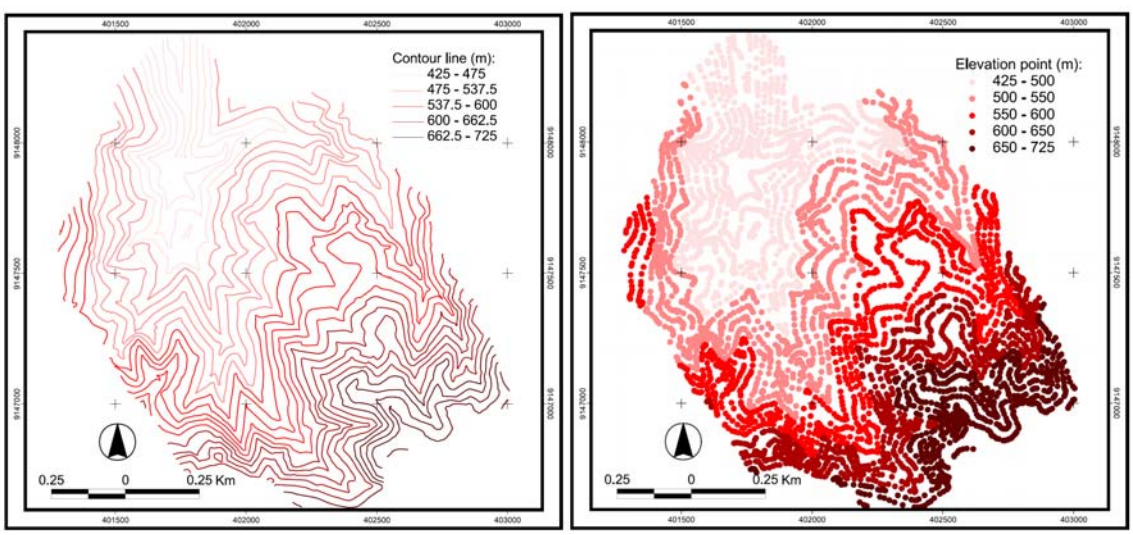


Figure 18 12,5m contour interval and elevation point

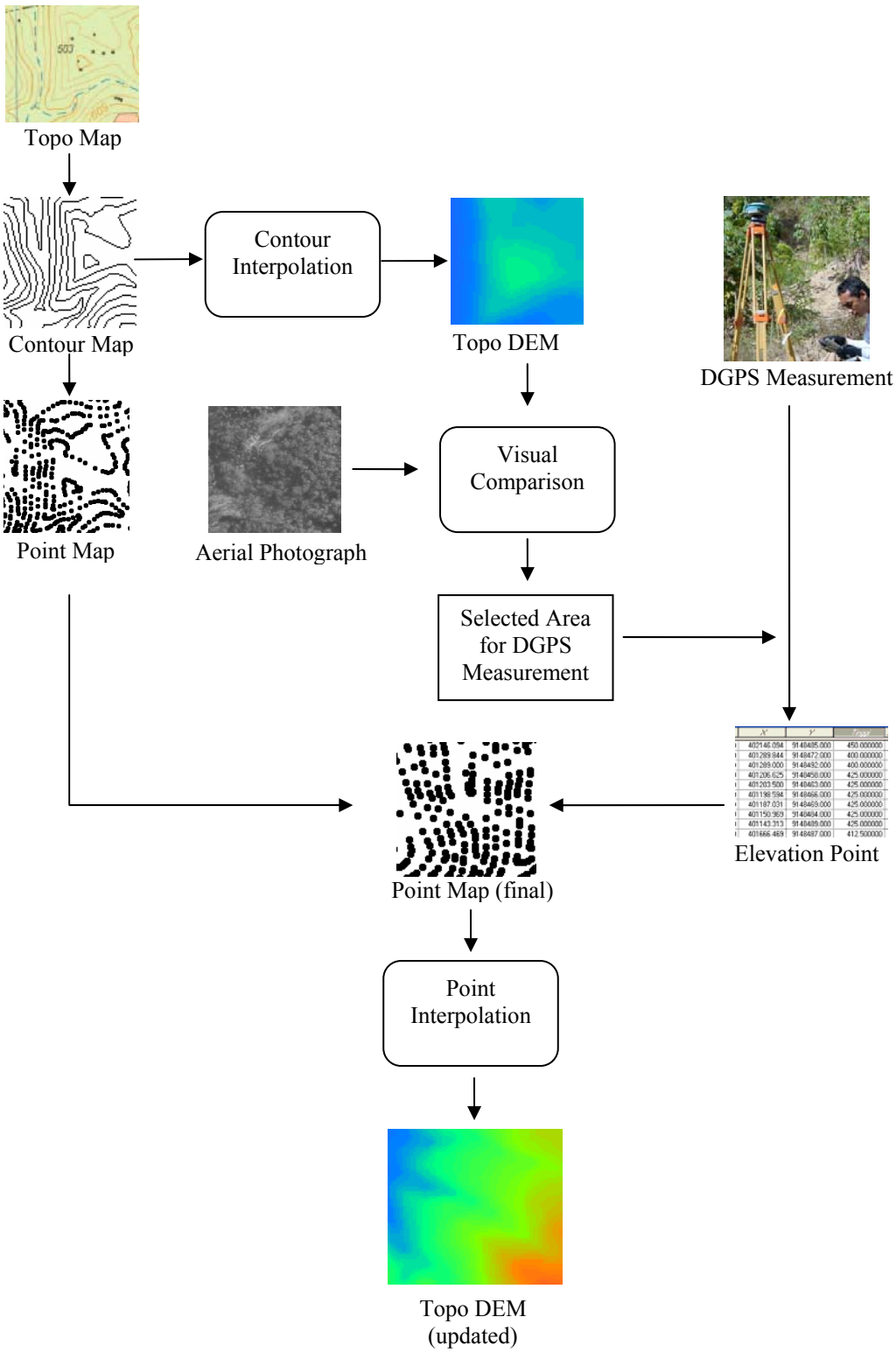


Figure 19 DEM Generation flowcharts

The resulting DEM was then analyzed whether it is good enough or not for model input. By comparing with the reality shape from aerial photograph stereo interpretation (visual comparison), we decide that the DEM result is quite good. But for some part the DEM result

shows a small difference with reality. There for, DGPS measurement and Laser survey was carried out to update the DEM in this area. Aerial photograph of year 2000 from MERAPI Project were used to define the ground control point. Figure 19 shows the schematic of DEM generation.

Trimble DPGS and SOKKIA DGPS were used to collect elevation point. This equipment has two GPS receivers. Figure 20 revealed to the schematic of DGPS data receiving processes. The first one is the base receiver and the other one is the rover. The base receiver was located in a fixed position which is already has a fixed coordinate. Since there is no reverence point in the research area which already published by Indonesian mapping survey agency, we define the point from the aerial photograph based on fixed object such as bridge or road junctions. Using this ground control point, we can start the DGPS measurement. In some locations which have no fixed object, the coordinate of the reference point was automatically generated from DGPS. The result of this measurement was elevation point.

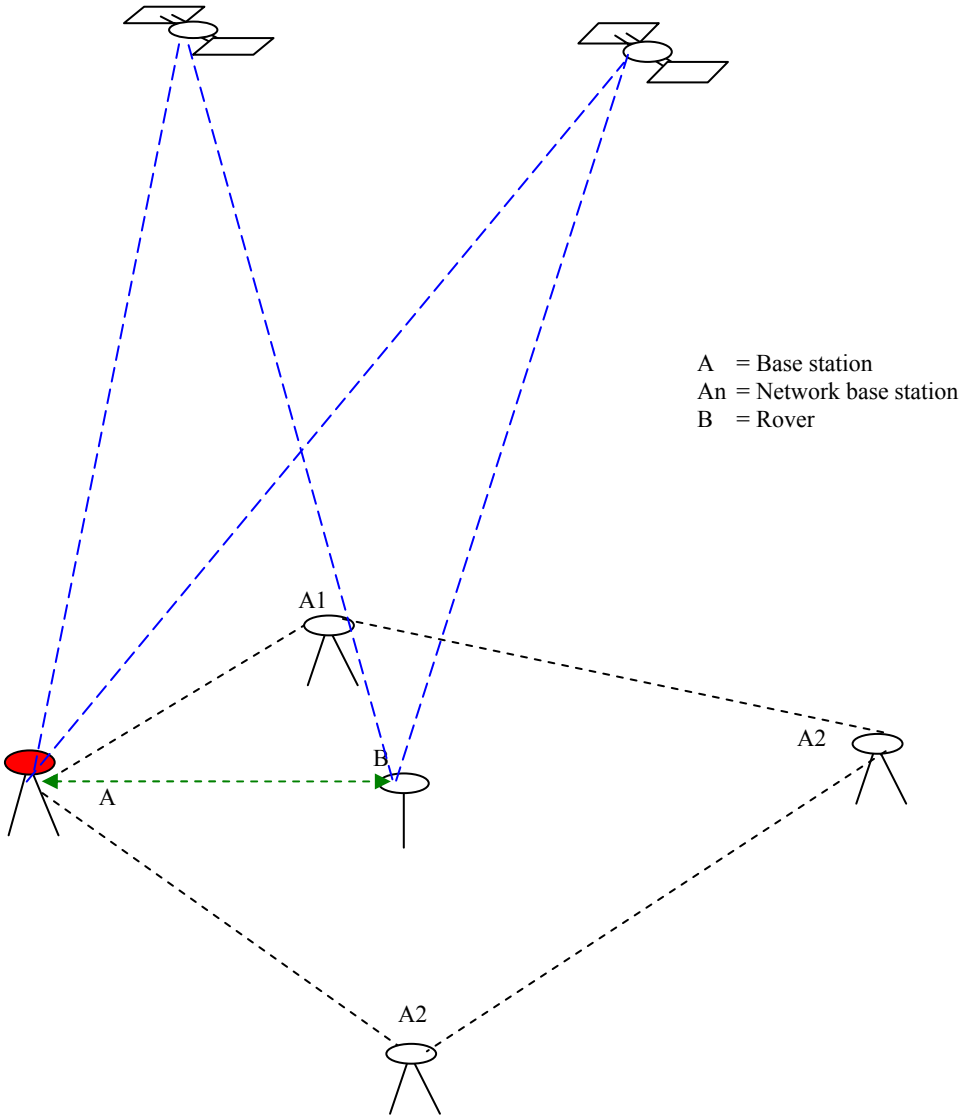


Figure 20 DGPS Systematic process
(adopted from SOKKIA user guide)

This DGPS can cover a large area. Unfortunately, the vegetation cover in this area is relatively high and it was often difficult to get signal from GPS satellites. In this situation, laser survey was applied. The laser survey was done from a fixed point from DGPS. The information of this laser survey was different in height, distance, and angle.

Terrestrial laser survey was used to collect elevation point in high vegetation dense area. From this measurement, we obtained information of a relative elevation. Relative elevation is different in height between the observation point and the reference point. To correct elevation of the observation point will be reference point plus elevation measured (equation 11). Figure 21 shows the schematic of manual laser survey.

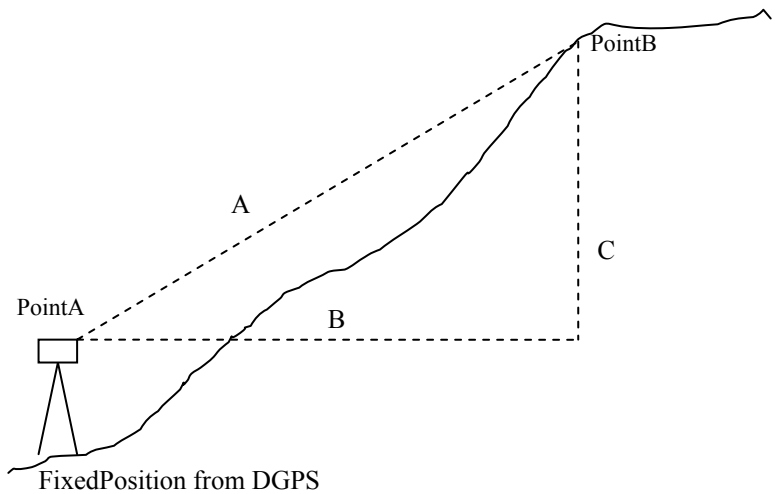
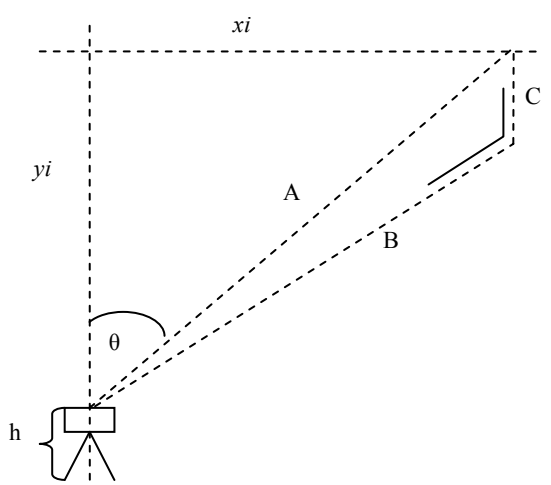


Figure 21 Manual Laser Survey

The coordinate of the observation point was generated from following equation (11, 12 and 13).



Where:
A = Inclination distance (m)
B = Horizontal distance (m)
C = Different in height (m)
θ = Inclination degree from north direction
yi = horizontal distance in Y direction
xi = horizontal distance in X direction
h = height of the laser

Figure 22 Manual Laser Surveys (2)

Figure 22 revealed to the schematic of the coordinate calculation of the observation point. Since manual laser survey has no coordinate recorded, the coordinate was calculated using equations 11, 12 and 13. The data from the laser survey was calculated using the equation below.

$$yi = \cos\theta \times A \quad (9)$$
$$xi = \sin\theta \times A \quad (10)$$

Coordinate of the point was defined by following equation.

$$Zn = Zref + h + C \quad (11)$$
$$Xn = Xref \pm xi \quad (12)$$
$$Yn = Yref \pm xi \quad (13)$$

where, *Zref* = Height of reference point
Yref = Y coordinate of reference point
Xref = X coordinate of reference point
Zn = Height of point number n
Xn = X coordinate at point number n
Yn = X coordinate at point number n

From the equation above we can get the coordinate of the observed point. The result was Xn, Yn, and Zn. Numbers of point was collected from this process.

Figure 23 Field measurement using Terrestrial Laser (1), Sokkia DGPS (2) and Trimble DGPS (3)

The new DEM was generated from a point map (Figure 18) in combination with the observation result. From the combining process, we can get a new point map. Point interpolation in ILWIS 3.4 was used to get a new DEM. Figure 24 shows the final contour map.

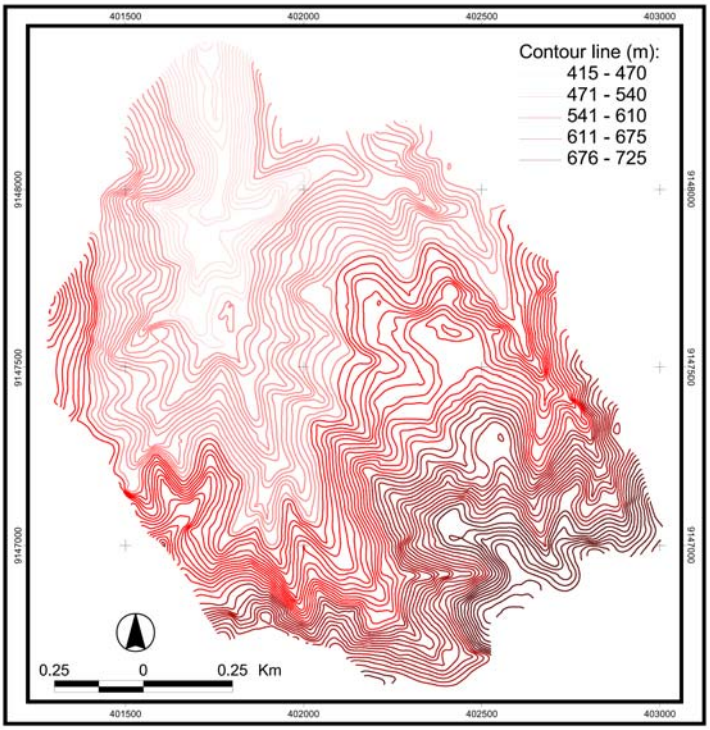


Figure 24 Final contour maps, 7.5 contour intervals

The final digital elevation model was created using point interpolation in the ILWIS software. Point interpolation performs an interpolation on randomly distributed point values and returns regularly distributed point values. In ILWIS, the output values are raster values. Moving average methods were used in the interpolation process. Moving average assigns to pixels weighted averaged point values. The raster-based DEM will be used in the most modeling in this research. The result of the final DEM was shown in Figure 25.

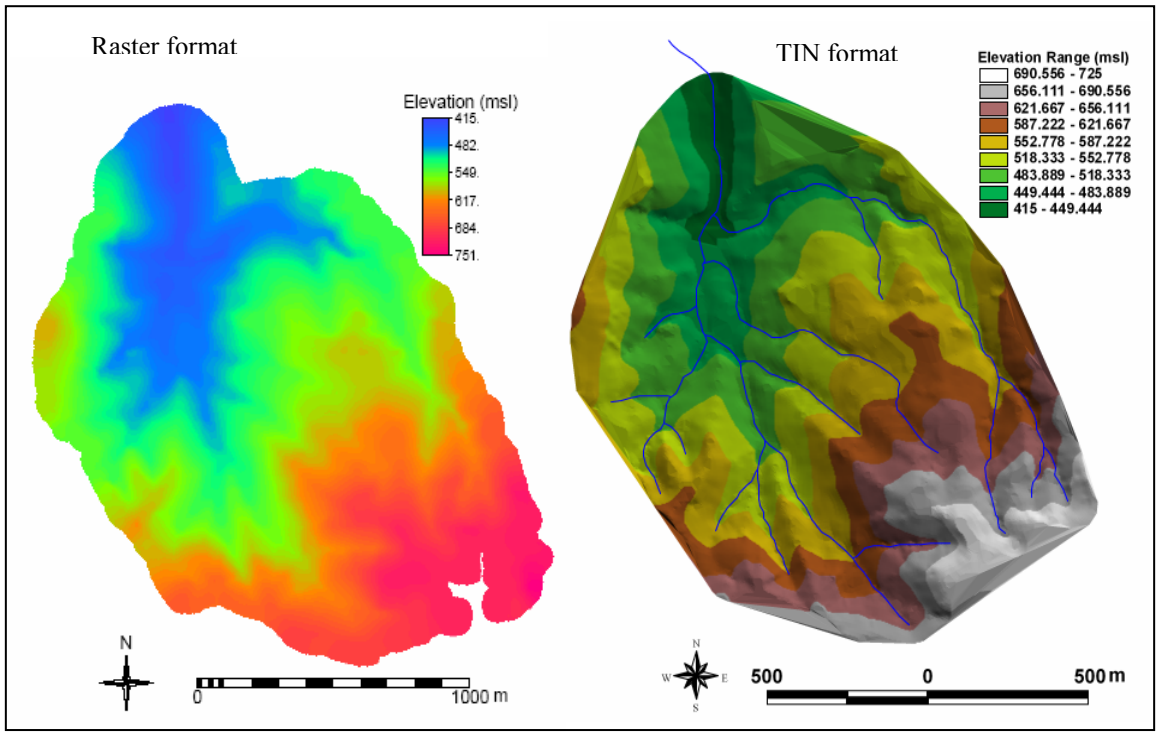


Figure 25 DEM format on ILWIS and Arc View Format (7.5 m resolution)
Dem of Sigebang Catchments (7.5m resolution, based on 1:25.000 topographical map of Purworejo and 1:20.000 aerial photograph of Perhutani)

4.2 Concluding Remarks

DEM has become one of important input for the Hydrological – Slope Stability Modeling. The effect of DEM resolution has a major impact on hydrological – slope stability modeling especially on slope calculation.

It was possible to optimize the DEM resolution of contour map from topographic maps using field measurement. DGPS measurement and laser survey was considered as best way to observe elevation head in the field. Those equipments were able to collect an accurate data and store in to data logger. Three main equipments used in this process were SOKKIA DGPS, Trimble DGPS and Manual Terrestrial Laser Scanner.

The limitation of this process was that the vegetation in the research area was very dense. DGPS data collecting was no longer applicable in this situation. Therefore, terrestrial laser survey was carried out. To measure whole catchments area will take too much time. Considering this condition, field measurement was applied only in selected area. The selected area was chosen by comparing the DEM from topographic map and the stereographic aerial photo interpretation (visual comparison). The area which have a significant different was selected. The other criterion was the area was feasible to do the field measurement. In this manner, the area which is remote and high vegetation dense was avoided. 4112 point was collected in this process.

DEM was generated from point interpolation. Contour map from topographic map was converted into point map. In combine with the observation point using DGPS and Laser Survey, the final point map was produce. The final point map was used to generate the final DEM. Point interpolation has been applied.

The result of final DEM shows a reasonable output. As compared to the previous DEM, there seem not so many differences. This can happen because the field measurement only done in a selected area with specific criteria. Therefore, so many slopes appear in a same impression with the topographic DEM.

5 Slope Stability Modeling

An integrated approach using GIS environment has been used to generate hydrological model. The PC Raster using STARWARS model has been used to calculate; perform and analyzed the hydrological condition on sloped area. STARWARS is a script model to do a simulation of hydrological processes in a sloped area. The result of this model will be used as an input for slope stability modeling in PC Raster environment using infinite slope method (PROBSTAB).

The model was very data demanding. Those data need to be converted into compatible type. The input data and the conversion discussed below.

5.1 Model Data Input

To perform slope stability model, spatial data and others input data were needed, i.e.

1) Land use,
2) Meteorological data,
3) Soil depth information,
4) Soil properties,
5) Topographic Dem and Slope Map,
6) Land use map, and
7) Landslide inventory map for validation.

Those data were used in form of map, table or time series data.

5.1.1 Rainfall Data

Daily rainfall data of Kaligesing rain gauge from 1990 – 2006 was used in this research. The model was run using year 2005 and 2006 rainfall data. The others 14 years data (1990 – 2004) was used to warming up the models. Warming up model was use the same script, same area and same parameters. What is different was the rainfall. In this process, 14 years rainfall data was used. This process was done to get the realistic initial soil moisture map and water table maps that were used as initial condition. Figure 26 and 27 shows the daily rainfall distribution 1990 – 2004 and daily rainfall during 2005.

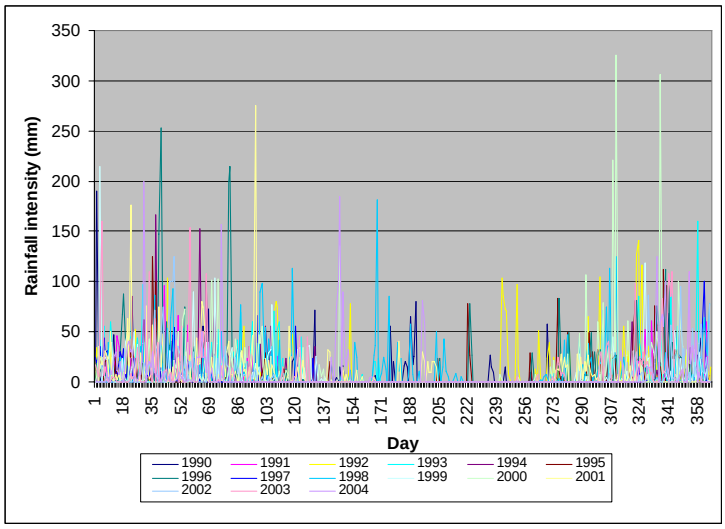


Figure 26 Variation of daily rainfall (1990 – 2004)

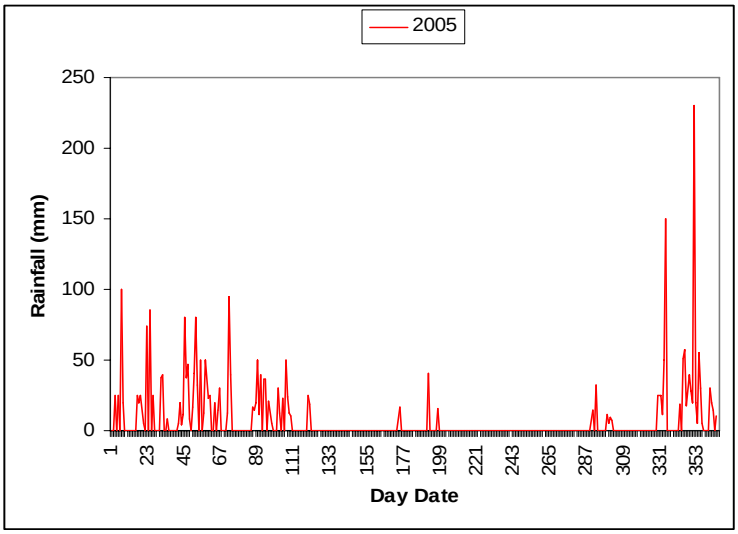


Figure 27 Rainfall amounts for the year 2005

The rain gauge near by the research area was limited. Therefore, the distribution of rainfall intensity was assumed the same for the whole catchments area. The data was collected from Kaligesing rain gauge. Table 7 shows the statistical analysis of rainfall intensity at 2005.

Table 7 Daily rainfall statistic for Probolo Sub-catchments (2005)

Year	Min	Max	Mean	Std. Error	Std. Deviation
2005	0	230	7.72	1.10	20.939

From the statistical analysis, we found that the maximum rainfall in 2005 was 230mm/day and the average was 7.72mm/day with standard deviation 20.939.

5.1.2 Land use

Land use was one of the important parameter in the landslide modeling. Soil physical properties might be different for a same soil type because of the land use.

The information of land use was generated from several sources, i.e. 1) Topographic maps in scale of 1:25.000 (2000), 2) Aerial photograph in the scale of 20.000 (2001) and 3) Participatory GIS. Figure 28 shows the land used map of the study area. Based on that, we found out that the dominant land use type was vegetation cover, typical people forest. This is varying in terms of vegetation type and height. Based on that, the land use classification was derived. The land use classification was:

a. Land use type 1, consist of *settlement* area (settlement, school, livestock, office and other building)
b. Land use type 2, consist of Secondary vegetation, (grasses, herbs, shrub, non permanent vegetation, fruit trees such as *Mahkota Dewa* (1-1,5m high), horticulture).
c. Land use type 3, consist of primary vegetation, (tall-growing species, coco trees, cloves trees, and other high vegetation).

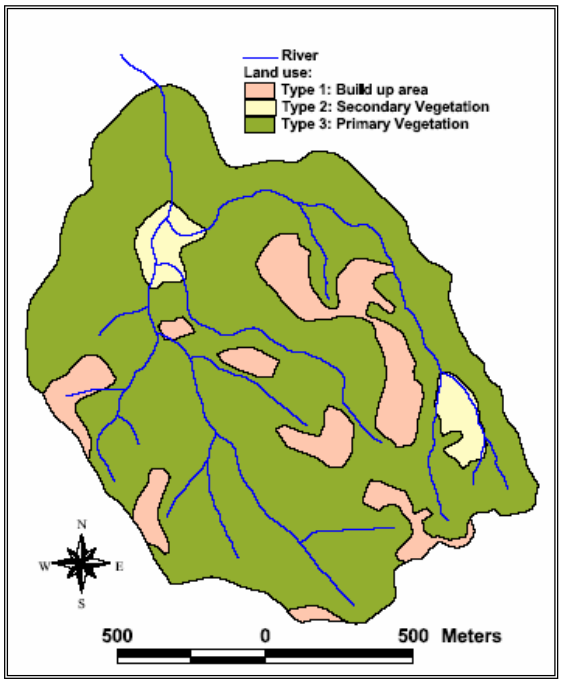


Figure 28 Combination of observed land use classes in tree units.

5.1.3 Meteorological Data

The meteorological data was used to derive potential evapotranspiration information. In order to get that information, Penman equation was used. The evaporation was derived from the sun radiation information and the intensity. Figure 29 revealed to the potential evaporation generated from Penman equation.

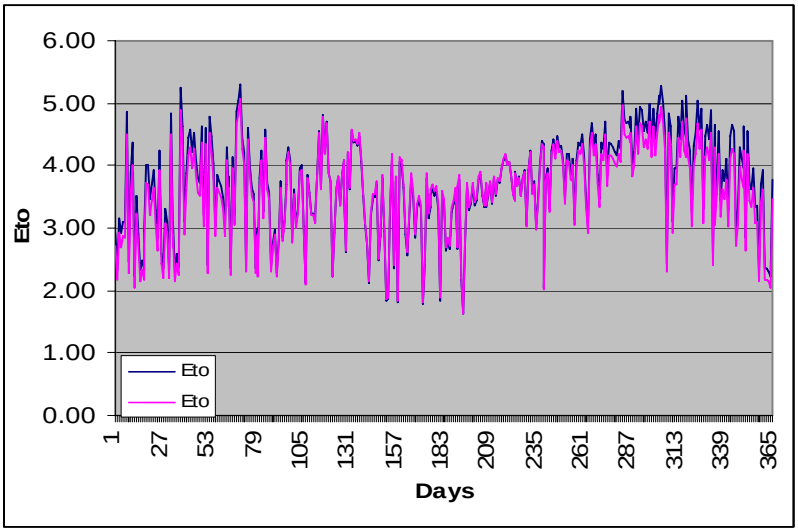


Figure 29 Potential Evapotranspiration of 2005

Table 8 shows the statistical information of Eto 2005. From that table, we found out that the minimum ETo was 1.64 mm and the maximum 5.06 mm with standard deviation was 0.72.

Table 8 Potential Evapotranspiration statistic of 2005

Year	Min	Max	Mean	Std. Error	Std. Deviation
2005	1.64	5.06	3.58	0.037	0.72

5.1.4 Soil Depth Information

Soil depth is the most important parameter for the models. It was used fro the two models, STARWARS and PROBSTAB. 108 investigation points were collected to determine the spatial information of soil depth (Figure 30). The investigation was done along the roads; rivers and valley (see section 2.2).

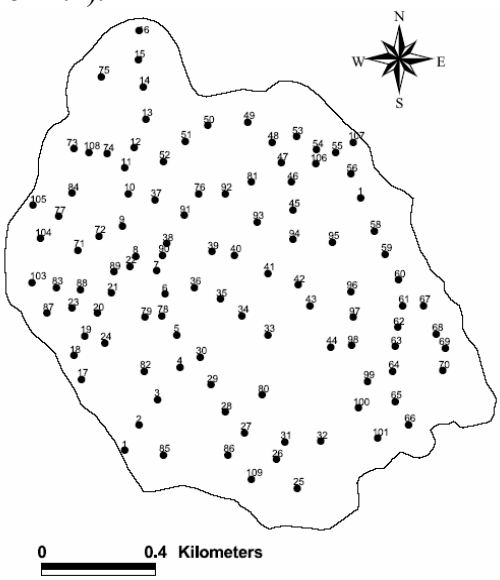


Figure 30 Sample distribution

The model required spatial information. It is difficult to get soil depth information at every location exactly. Therefore, point interpolation was applied. Point interpolation performs interpolation on randomly distributed points and return into regularly distributed value. Moving average and kriging was compared. The best result was used to run the models. In Ilwis, Moving average was point interpolation which performs a weighted averaging on point value and return into a raster maps as an output. Figure 31 a shows the result of moving average method. The other method was kriging. Unlikely moving average, kriging was based on statistical methods. In Ilwis, kriging was the only methods which give us the interpolation result and output error map with standard error of the estimation. Figure 31 b show the result of kriging interpolation.

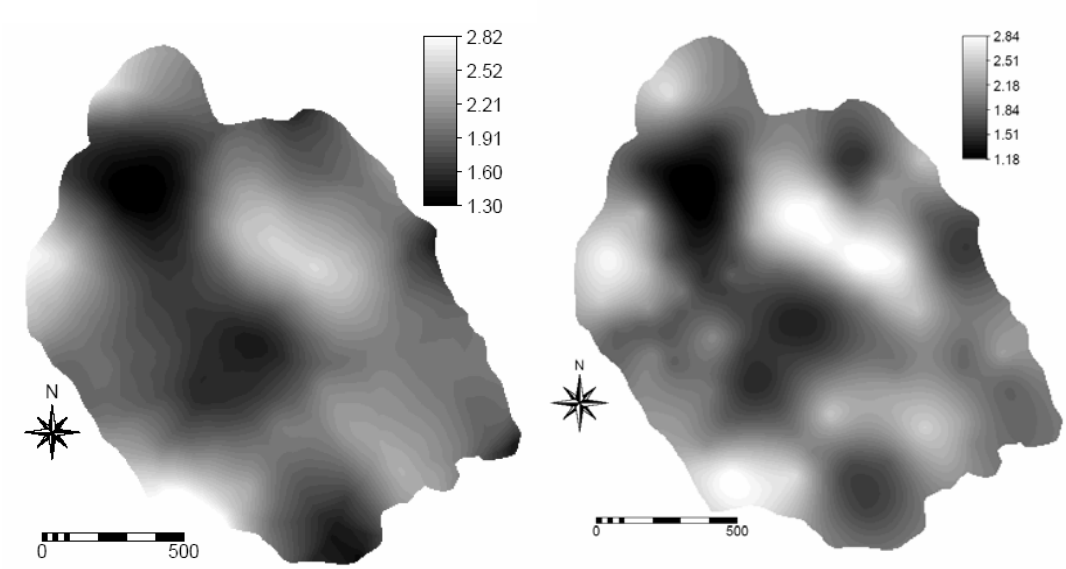


Figure 31 Soil depth spatial information,
a) moving average method b) Kriging Method.

Table 9 Soil depth statistical analysis.

	Min	Max	Avg	Stand. deviation	Sum
Mov avg	1.22	3.32	3.27	0.61	487.97
Kriging	1.04	3.01	2.03	0.57	400.95

The shallowest soil depth based on the observation was 0.70m and maximum 3.25m.

5.1.5 Soil Properties

12 soil sample was collected both disturbed and undisturbed soil sample (appendix 5). The sample was collected on different soil type. For the define polygons, the saturated hydraulic conductivity, the porosity and dry bulk density was studied. 12 undisturbed soils samples were collected to obtain the geotechnical information. Triaxial test and shear box analysis was carried out. The result (Table 10) was used to define the slope stability of the catchments using infinite slope model.

Table 10 Geotechnical parameters.

No	Sample	c	Φ
1	1	71	32.5
2	2	71	31.8
3	3	92	28.5
4	4	48	34.6
5	5	99	19.4
6	6	10	18.2
7	7	85	27.5
8	8	43	31.3
9	9	87	26.4
10	10	67	19.1
11	11	43	22.4
12	12	75	21.6

5.1.6 Topographic, DEM and Slope Map

In the models, topography is represented by a digital elevation model (DEM). Digital Elevation Model for this research was developed from Topographic Map and DGPS measurement (*see chapter 4*). Information of DEM was very important for Hydrological – Slope Stability Model.

5.1.7 Landslide inventory map

Landslide inventory map was derives by PGS process and filed check (*see chapter 2).* Since the landslide inventory data was not available, PGIS seems the best method to get that information. Unfortunately, peoples only notice the landslides which form a hazard. The others landslide, the natural phenomena, they forget.

5.2 Performing Hydrological – Slope Stability Model

The file input for the modeling was 5 meter pixel resolution for each map. With 377 rows and 379 columns, the file size was 559Kb for each map files. Figure 32 shows the research flowchart for the hydrological – slope stability modeling.

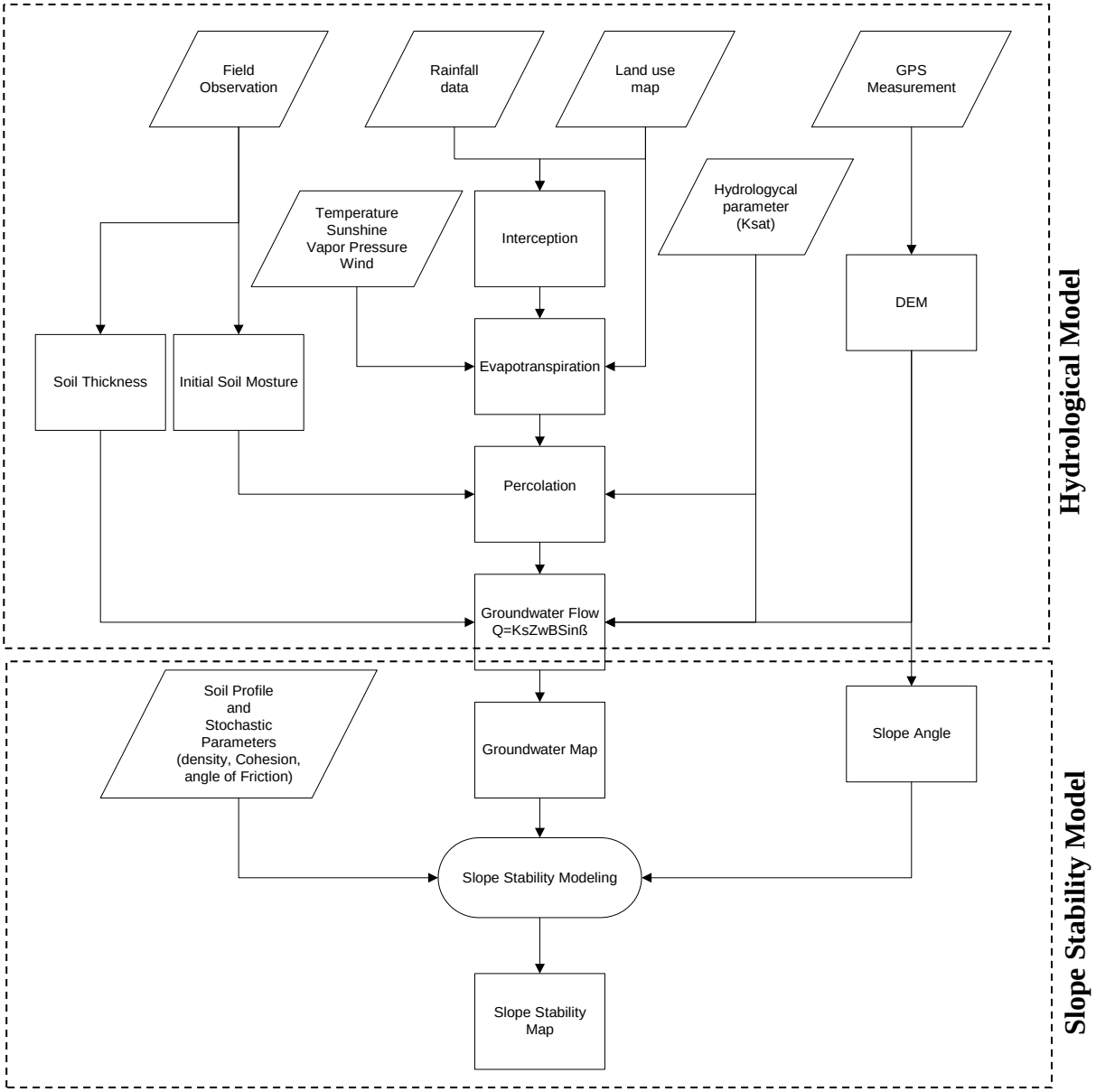


Figure 32 Flow Chart Methodology for Hydrological and Slope Stability Modeling

5.2.1 Hydrological Model (STARWARS)

The model was setup to run in years 2005. This model was tried to provide spatial and temporal information of water level.

5.2.2 Result of STARWARS

The model was run in years 2005. Figure 33 shows the variation of water level at years 2005. Warming up model was done to get the initial condition of the area for the real models. The warming up was about 14 years (1990 – 2004). The warming up model was carried out with assumption that the condition of the entire catchments will remains the same as the condition at 2005. The result of the last day of 2004 was reported and used as an initial condition for the real model (2005).

Figure 33 shows us the spatial and temporal distribution of the water level in the study area. From the figure, we can see clearly that the spatial distribution was varied due to temporal resolution. Even though, the maps show not much different in term of spatial pattern. The similar pattern was appears in a specific same time (same rainfall, give a same pattern).

Table 11 Statistical data of simulated water level (2005).

No of day	Min	Max	Avg	SD
1	0.00	2.99	1.454	0.587
32	0.00	3.01	1.397	0.584
63	0.00	3.01	1.639	0.505
94	0.00	3.01	1.538	0.576
125	0.00	3.01	1.525	0.557
156	0.00	3.01	1.454	0.575
187	0.00	3.01	1.689	0.482
218	0.00	2.99	1.368	0.586
249	0.00	3.01	1.436	0.580
280	0.00	3.01	1.456	0.575
311	0.00	2.98	1.308	0.587
342	0.01	3.01	1.757	0.440

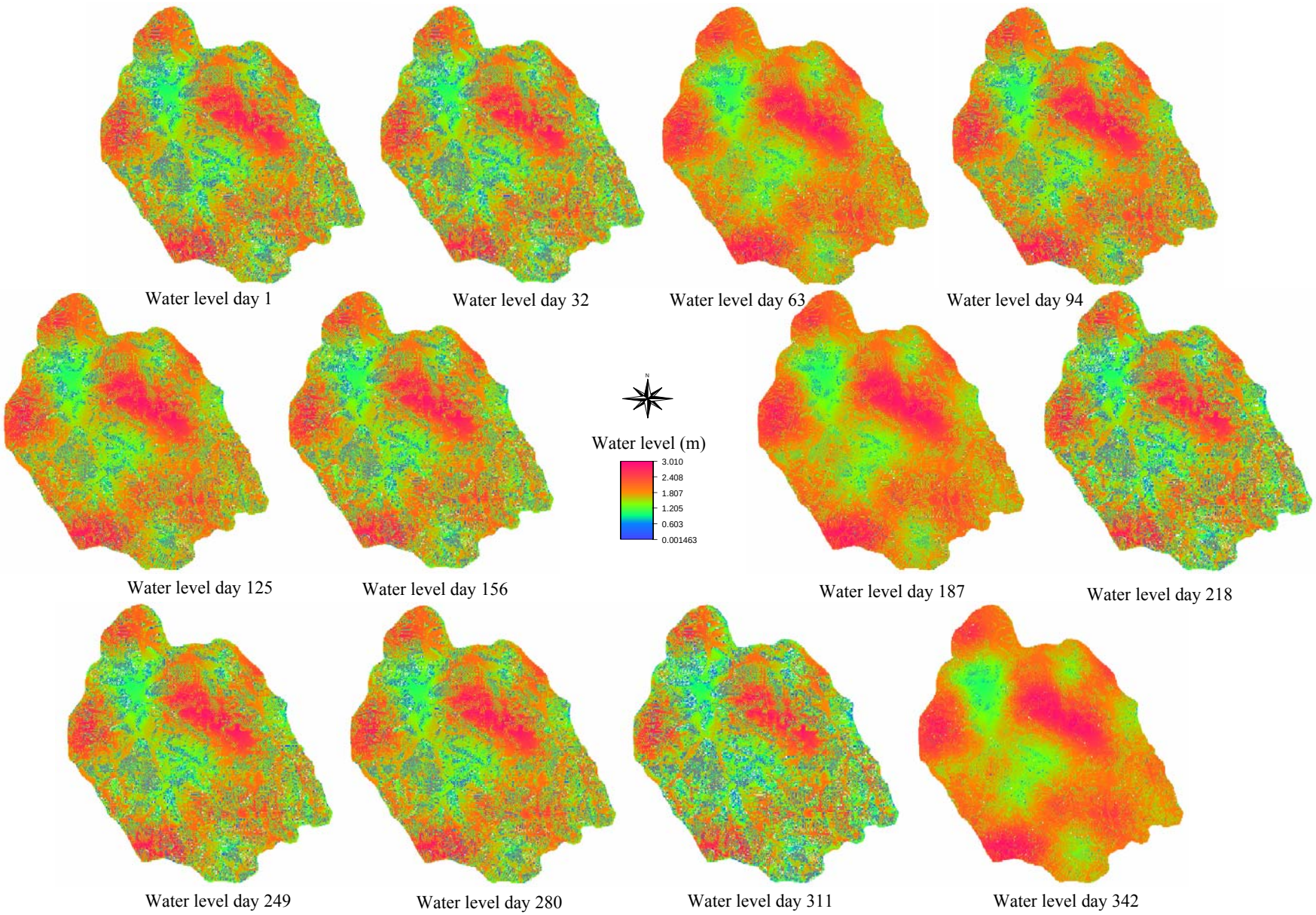


Figure 33 Simulated water level year 2005

The result shows an interesting number. Table 11 shows the variation of the water level in minimum, maximum, average and standard deviation. From the table we found out that the minimum average was happen at day 32 (February) with 1.397m. The maximum value occur at day 342 (December) with 1.757m. Figure 34 shows us clearly the spatial distribution of water level in the study area. The maximum value of the water level might shows that the model was over estimating. For the whole years, the maximum water level was around 3m. With the soil thickness average of 3m, the slope was already collapse before the water level reach 3m depth. This condition might shows an over estimating by the model.

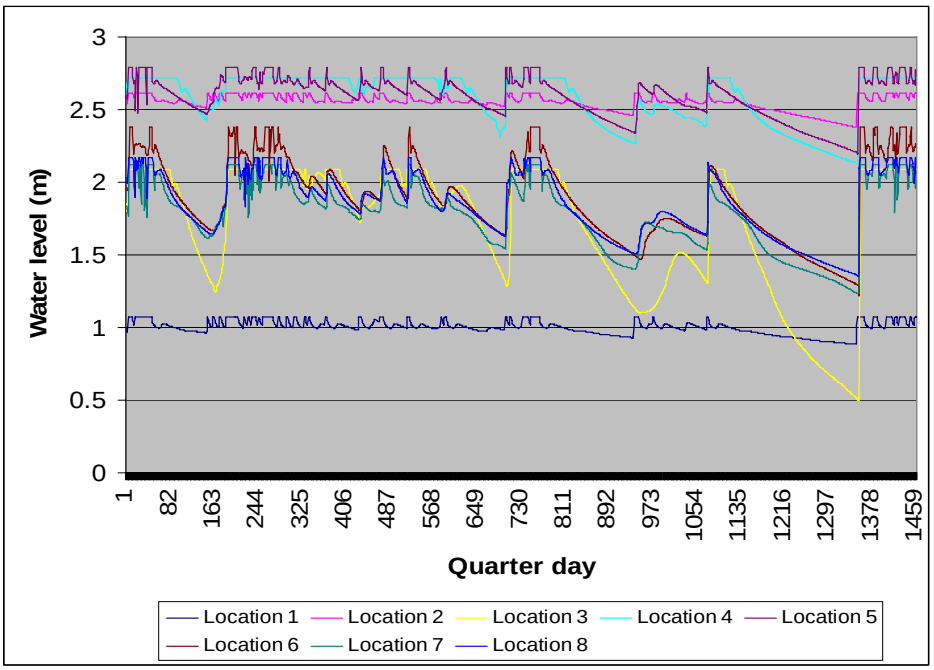


Figure 34 Simulated water level in year 2005

Figure 34 shows us the water level fluctuation in different time. From the figure, we can see clearly that the water level was extremely different for each point. Even tough the graph shows a different in terms of value, but still it was appearing the same in term of pattern.

5.2.3 Slope Stability Model (PROBSTAB)

PROBSTAB script in PC Raster environment provides slope stability model using infinite slope methods. This script was developed by Van Beek (2002) and modified by Sekhar (2006).

5.2.4 Result of PROBSTAB

As well as STARWARS, PROBSTAB was set to run for the year 2005. The slope stability was classified into 3 classes, < 1, 1 – 1, 5 and >1, 5. The STARWARS results were used in the slope stability modeling to calculate pore water pressure. Figure 35 shows the daily variation of safety factor simulated by PROBSTAB. The pattern was nearly the same time to time. This indicated that the area which have slope stability problem remains the same over most of time.

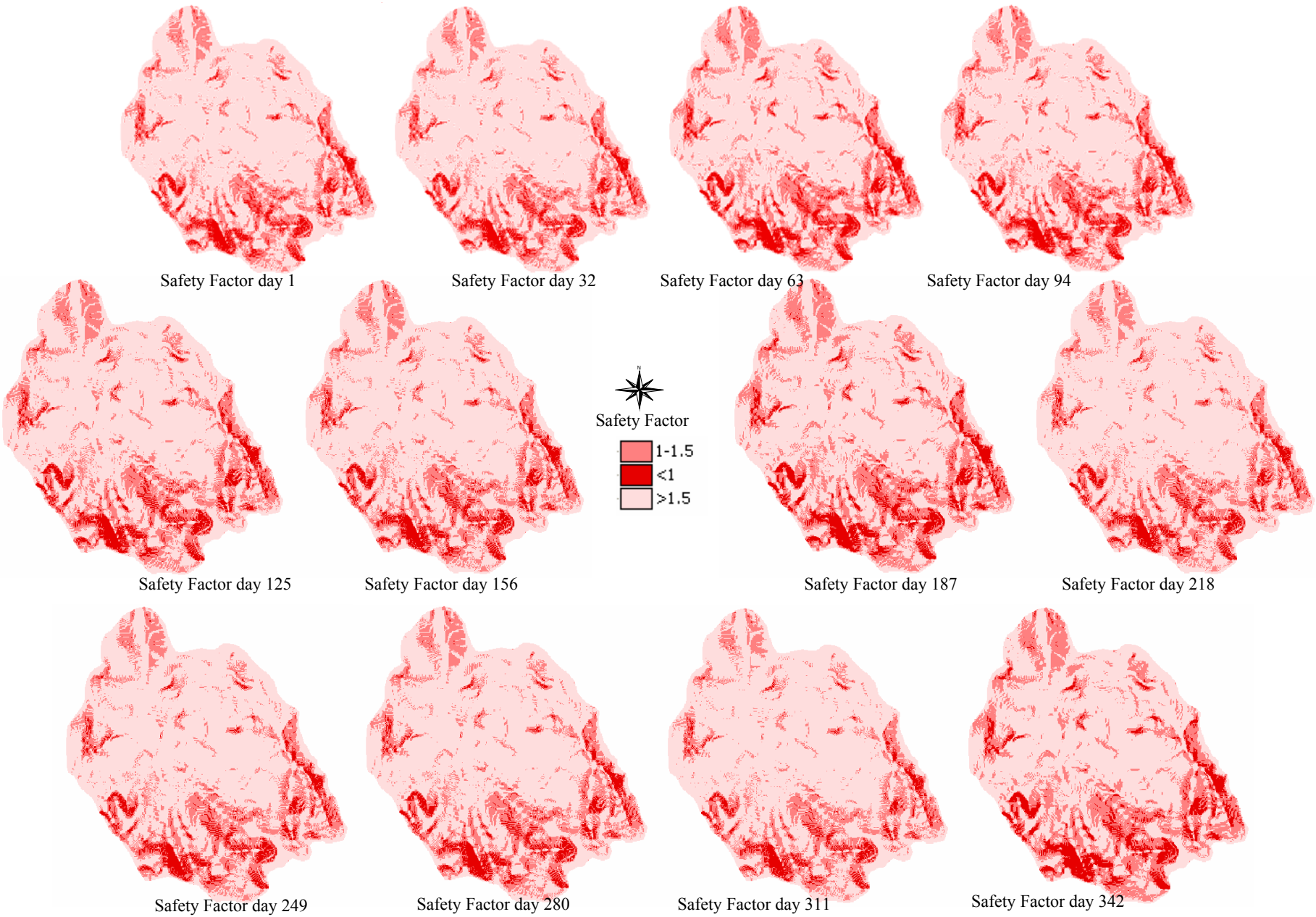


Figure 35 Time series of simulated safety factor from PROBSTAB

The model did predict the known location of instability as unstable area. In the figure 35 shows the model predict the instability (fs≤1) was quite good. The model estimated almost the same location which have stability problem. What is different in time was the area for each class. The different can caused by the different of the rainfall intensity.

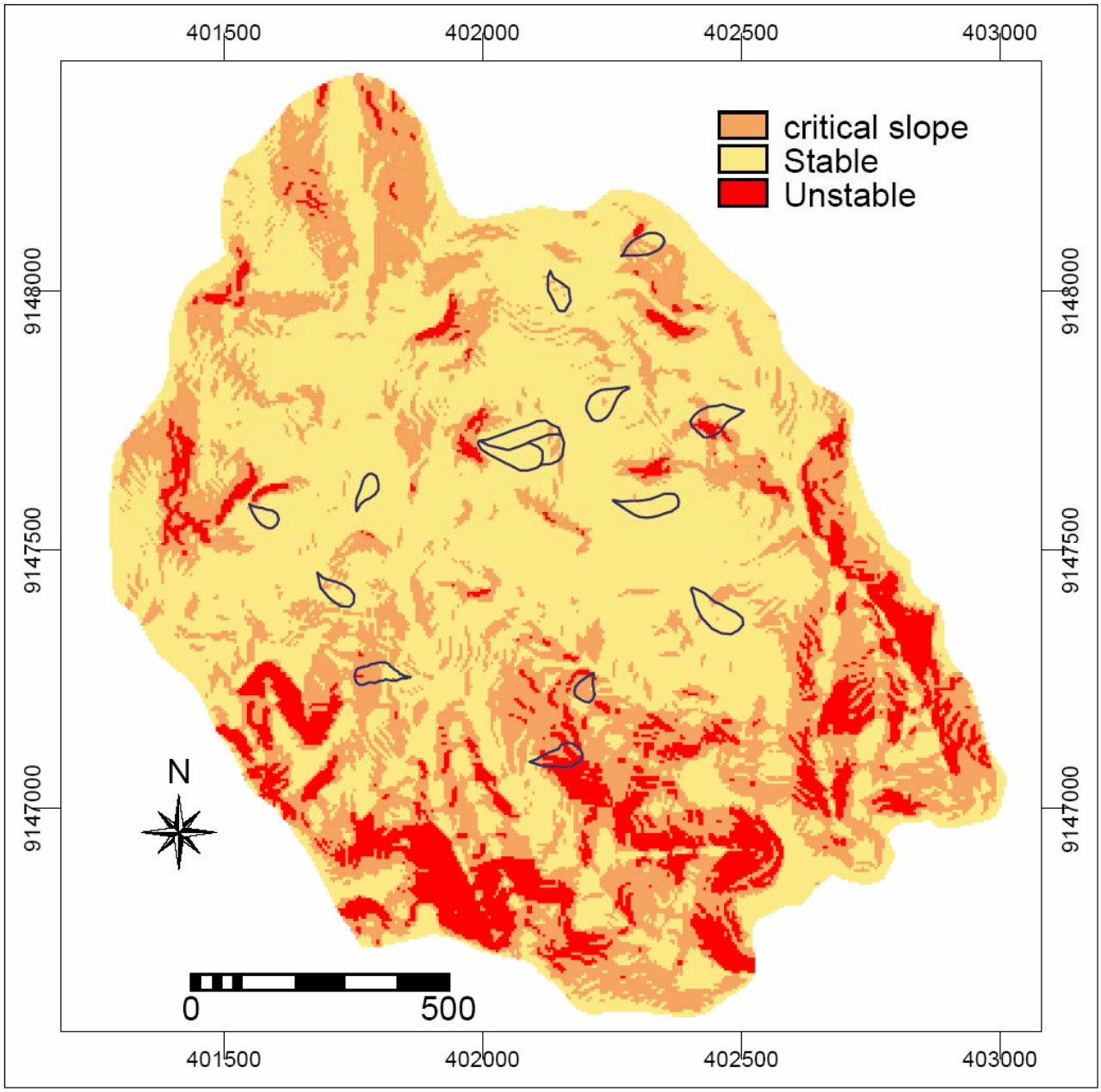


Figure 36 Overall slope stability classes during 2005

Figure 36 shows the overall slope stability of the study area based on the maximum safety factor scored on each pixel for 2005. Figure 37 shows the daily variation of slope stability. The model has predicted area of unstable 221275m^2 or 0.22km^2 areas.

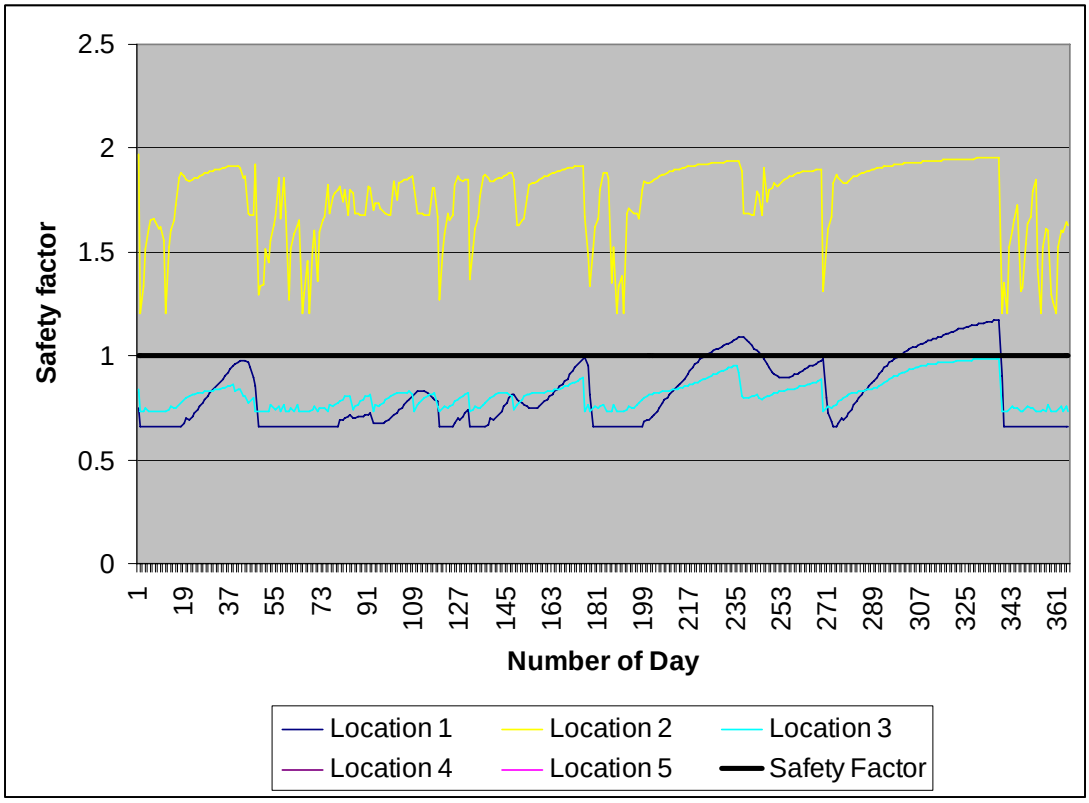


Figure 37 Daily variation of safety factor during 2005

Figure 37 shows the variations of slope stability in different time. From the figure, we can see clearly that the slope stability was extremely different for each point. Even tough the graph shows a different in terms of value, but still it was appearing the same in term of pattern.

Table 12 Statistical data of the simulated safety factor

No of day	Min	Max	Avg	SD
1	0.549	≥3.5	1.81	0.674
32	0.567	≥3.5	1.898	0.683
63	0.545	≥3.5	1.814	0.674
94	0.552	≥3.5	1.848	0.675
125	0.549	≥3.5	1.849	0.677
156	0.549	≥3.5	1.875	0.676
187	0.530	≥3.5	1.798	0.669
218	0.563	≥3.5	1.911	0.678
249	0.567	≥3.5	1.882	0.675
280	0.546	≥3.5	1.872	0.677
311	0.567	≥3.5	1.935	0.677
342	0.529	≥3.5	1.785	0.670

Table 12 shows the statistical information of daily simulated slope stability. From the table, we can conclude that the study area was facing slope stability problem for whole of the years.

5.3 Concluding Remarks

The STARWARS results show the water level was fluctuating due to different rainfall intensity. So far, the information of the actual water level was not available. By this condition, the calibration of the result to the real condition can not be done. Since the information of water level was very important to determine the developing of pore water pressure, the result was considered as a good result. In this manner, we just use the result for the slope stability modeling. Consequently, the performance of the slope stability will be impaired by uncertainty as the model inputs was data that insufficiently tested.

The result from STARWARS shows the maximum water level was 3.01m. This condition almost occurs for the whole years. This means that for some location, the water was saturated and difficult to be drained. Before the soil was drained, the rain was occurring and the soil was saturated again. Figure 35 shows the temporal resolution of water level fluctuation. Figure 36 show the pattern of water levels fluctuation during 2005. The result of this modeling was used to calculate the developing of pore water pressure. More over, it was used as an input for slope stability modeling of PROBSTAB.

PROBSTAB script was used to predict the slope stability using infinite slope method. The susceptibility of the area to slope failure can be expressed by means of safety factor. Probabilistic model of PROBSTAB, predict 11.32% of the entire area was susceptible to slope failure. Figure 37 shows the temporal resolution of simulated slope stability. Figure 39 shows the fluctuation of safety factor in 2005. The result of slope stability modeling was divided into three classes (Figure 38). They are Stable slope, critical slope and unstable slope. From the analysis, 11, 32% was unstable; 31, 86% was critical and 56, 82% was stable slope.

6 Landslide Hazard Assessment

Landslide hazard assessment was figured on a landslide probability map. Varnes et,al (1984) define landslide hazard as "probability of occurrence within a specific periods of time and within a given area of potentially damaging phenomenon". In this chapter, we purpose a landslide hazard assessment using probability failure from PROBSTAB.

6.1 Landslide Probability

When we are dealing with landslide hazard assessment, we are dealing with uncertainty. Not as other hazard type, in landslide, it was difficult to assess the magnitude, return period, etc. in this manner, probability modeling was one of consider powerful method to assess the uncertainty. Probability is a numerical measure of *our* uncertainty regarding nature. More over, Probability models are used for purposes of description and prediction of physical processes in nature. These models used an approach to deal with the limitations to our knowledge of natural processes.

The probability occurrence of landslides can be calculated by using the prior probability developed by Bonham-Carter et al (1990) in Van Westen (1993). This method based on the presence and absence of the landslide event in the each pixel or terrain unit, within the formula:

$$P_p = \frac{Npix(slide)}{Npix(total)} \quad \text{.....} \quad (14)$$

in which :
P = spatial probability
Npix (slide) = the number of pixels occupied by landslide or unstable area
Npix (total) = the total number of pixel in the map.

PROBSTAB simulated 8851 pixel to be unstable from the 69997number of pixel. Using equation 14, we can calculate landslide probably in term of landslide density.

The simulated probability will be:

$$P_p = \frac{8851}{69997} = 0.127$$

From the PGIS process and field observation, we found at least 15 landslide incidences. That entire landslide was a typical of hazard. Starting date from 1990 up to 2005. Based from those processes, we determine that the landslide in the area was 1644 pixel from 69997 number of pixel. Based from this information we can calculate the landslide probability/density.

The actual probability will be:

$$P_p = \frac{1644}{69997} = 0.024$$

The results shows a significant different. This condition can be caused by the information of inventory landslide which is only the landslide that forms as a hazard. The other landslides were not included in the inventory map. Therefore, the calculation of landslide probability using actual incidence has a biased effect.

6.1.1 Landslide hazard assessment

Original PROBSTAB has been modified and combined with FOSM to assess the spatial probability (Sekhar, 2006). Normal distribution has been use to assess the probability of failure. Based on the normal distribution, if the given area had an average probability of only 50% to fail, in relatively, they failed.

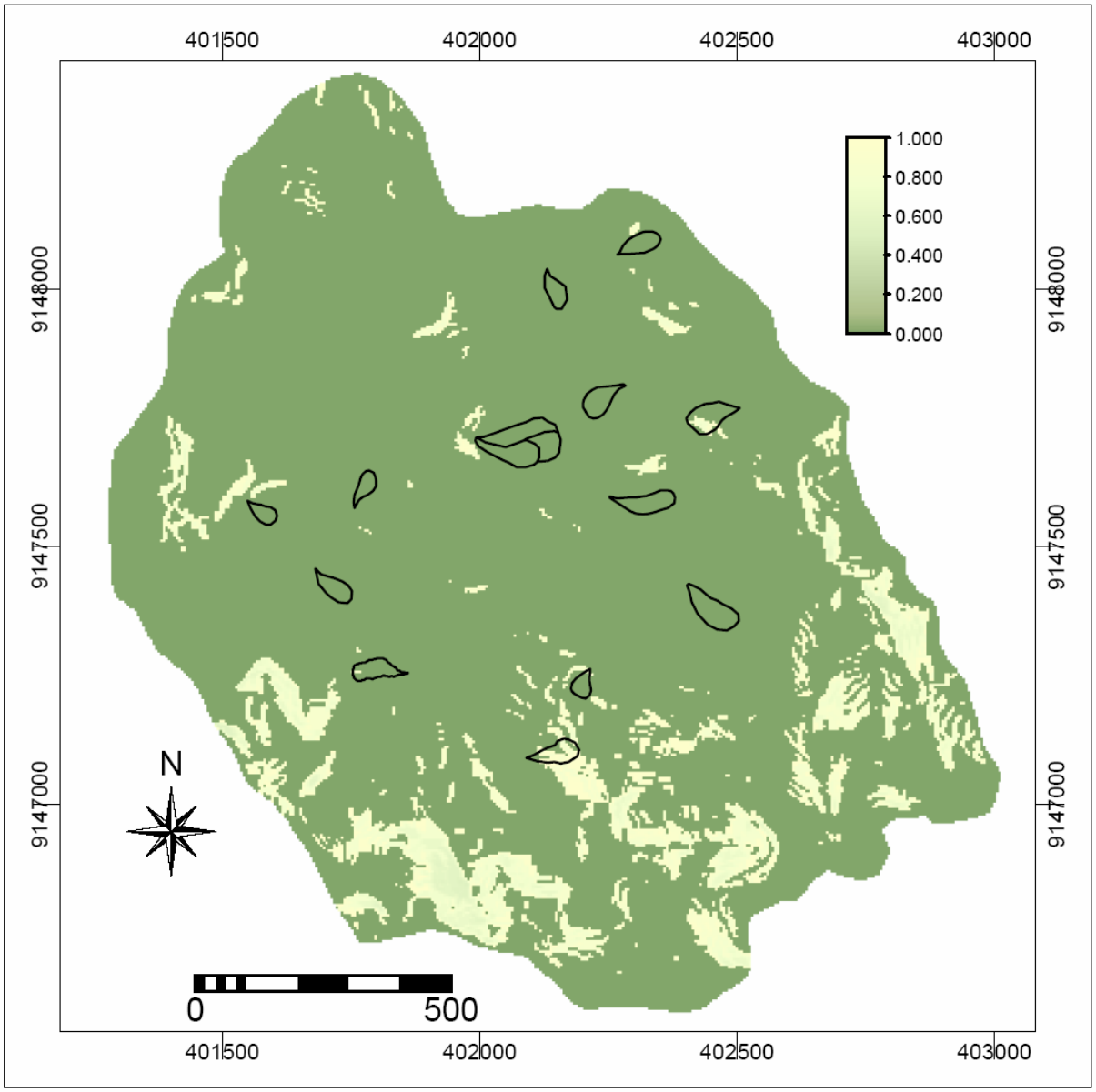


Figure 38 Overall simulated probability of failure for area with FS<=1.

Figure 38 shows overall probability of failure for area with FS<=1. The result brings 11.32% of the entire area has probability <1. They basically located in the upper part of the catchments area which is has a steepest slopes.

Probability map was considered as a good way to present the landslide hazard map. It wills answer the definition of landslide by Varnes et al (1984). It will give us the probability of occurrence within a specific of times, and a specific area of potentially damage. Figure 37 shows the temporal probability of occurrence either the spatial probability. Figure 40 shows the overall probability during 2005.

6.2 Concluding Remarks

This chapter deals with landslide hazard assessment. The application of hydrological – slope stability modeling using PC Raster simulation is aimed to producing landslide hazard maps which give the spatial and temporal failure probability of slopes.

The results brings 11.32% of the area were susceptible to landslide. Unstable slope generally located in upper part of the catchments area which has a steeper slope. The probability calculation shows the simulated failure and observed failure probability was significantly different. In fact, the simulated was higher then the observed. This condition might caused by the poor of landslide inventory map. Poor quality of data input might be one of the caused. The process of DEM generation which brings a final DEM which is quite the same with the previous DEM is one of the causes.

Only in those case when high quality input of data are available and the triggering mechanism are understood and modeled properly, a reliable estimation of failure may given. When working an landslide hazard assessment project with low quality of landslide inventory maps, no boreholes data are available, limited geotechnical information and hydrological parameters, the calculated failure probability should at first interpreted as relative measurement.

7 Validation and Evaluation of Results

7.1 Model Validation and Calibration

Validation of the results model was very important to understand how precise the models predict the natural process. Moreover, the validation plays an important role to evaluate the models. How good were the models? Is the input for the models good enough? What have to do if we want to run the models again and get better results? Can the models be applied in the other locations/areas? One of several ways to evaluate the model was a sensitivity analysis.

The sensitivity of the model to changes in the parameterization can be studied by means of sensitivity analysis (Kirkby, 1993). In sensitivity analysis, parameter inputs for the model were varied and the model outcomes were compared. The variation was done for each parameter. For each run, only one parameter was changed. From the results of the sensitivity analysis, the most influential parameters can be identified. These factors can consequently calibrate the models.

7.1.1 Sensitivity of STARWARS

The sensitivity of the STARWARS models was done in whole of catchments. Starting with the same initial condition, the result for the different input was analyzed. Therefore, we can understand how the parameters influence the model.

To assess the sensitivity analysis, several input were changed. The only inputs that remain the same for whole run were rainfall intensity. The models were analyzed as response of changes in for parameters. The model was run in several times with different input and the result was analyzed. The parameters are saturated hydraulic conductivity, porosity, soil moisture content at field capacity and soil depth.

The parameter change that has been imposed in the models have been calculated by adding and subtracting 25%, 50% and 100% of the standard deviation to the means parameter value. The sensitivity analysis shows the response of the models as a result of changing the inputs. Table 13 revealed to result of sensitivity analysis for each parameter. Figure 39 shows the sensitivity of the models as product of changing the inputs.

Table 13 STARWARS Sensitivity analysis parameters

	Ksat			Porosity			Alpha (SWRC)	Z (soil depth)
Layers	I	II	III	I	II	III		
Mean	0.67	0.21	0.013	0.5	0.5	0.5	9.52	1.89
St. Dev	0.18	0.038	0.0025	0.025	0.025	0.025	0.15	0.89

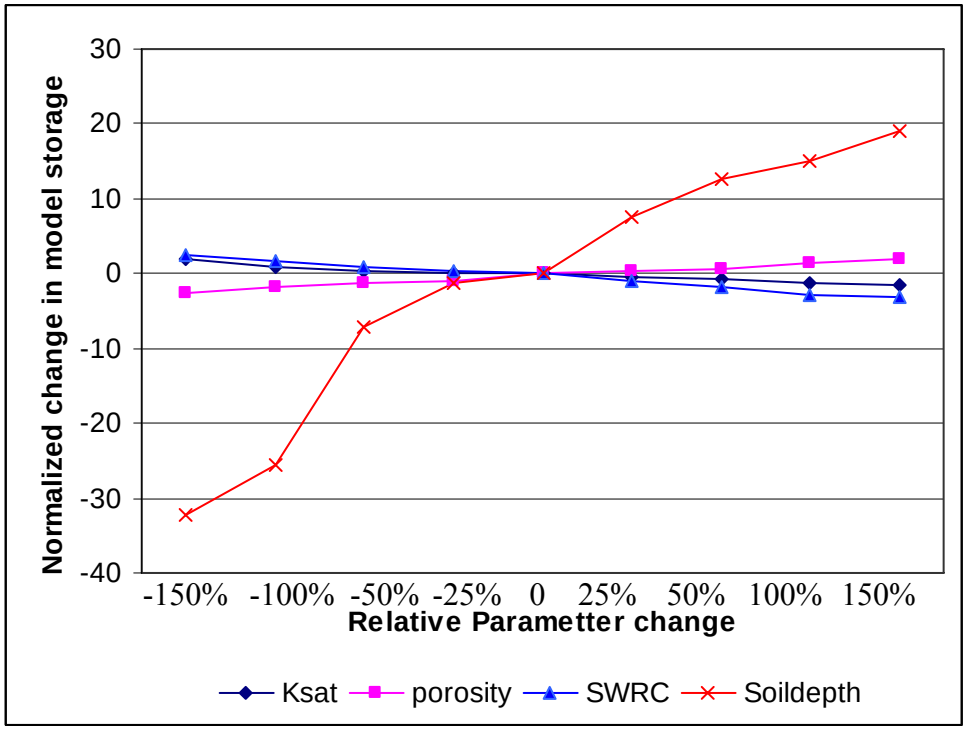


Figure 39 Sensitivity of simulated hydrology

Sensitivity of simulated hydrological condition was presented in figure 41. In term of total storage from the model, soil depth was the most sensitive parameters. The total storage was increases rapidly as the soil depth increases. In contrast, the storage decreases rapidly as the soil depth was deceases. Figure 41 clearly shows the influence of soil depth in the model. The other parameters were less influential as compared to the soil depth.

Porosity has been the next sensitive parameter. The storage was increases due to increasing the porosity. In contrast with soil depth and porosity, Ksat and soil water retention curve (SWRC) was decreases as the parameters increases. From Table 14, we can understand clearly the resuly of sensitivity analysis.

Table 14 Results of STARWARS sensitivity analysis

	Ksat	Porosity	SWRC	Z
	changing in %			
-150%	1.9	-2.6	2.4	-32.3
-100%	0.9	-1.8	1.6	-25.4
-50%	0.2	-1.2	0.8	-7.2
-25%	0.1	-0.9	0.4	-1.3
0%	0	0	0	0
25%	-0.6	0.4	-0.9	7.6
50%	-0.8	0.7	-1.9	12.6
100%	-1.1	1.4	-2.8	15
150%	-1.5	1.9	-3.2	19.1

Based on the sensitivity analysis, soil depth was considered the most sensitive parameters. The result of simulated soil depth was calibrated using field check. Figure 40 show the scatter plot of the observed and simulated soil depth.

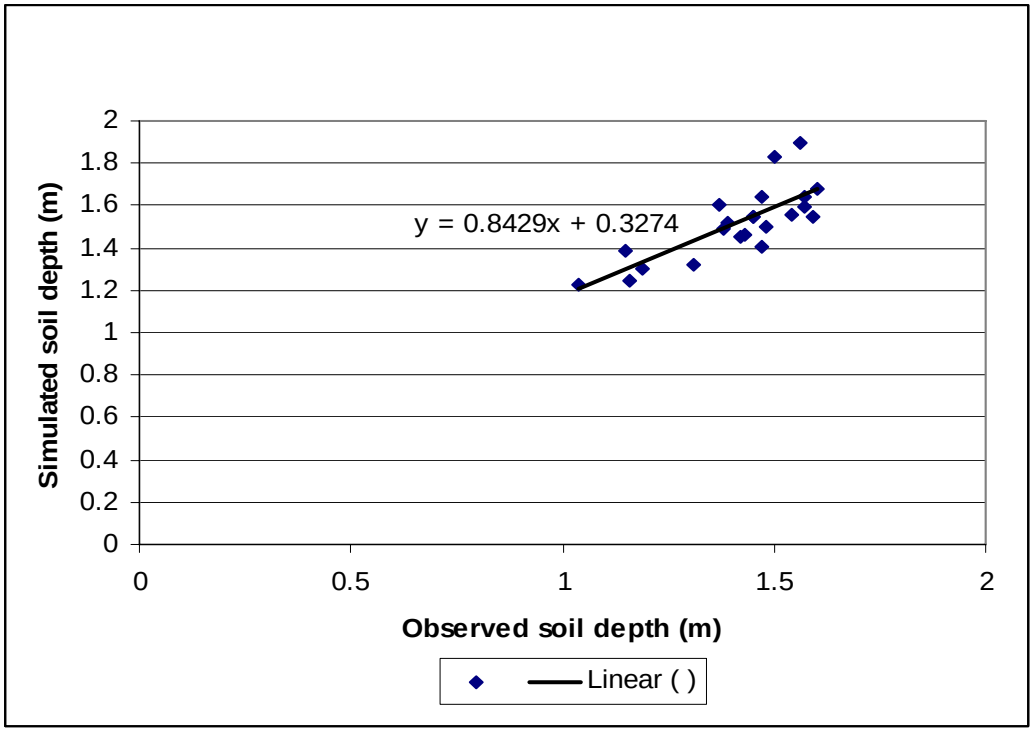


Figure 40 Simulated and observed soil depth of Probolo sub-catchments

7.1.2 Sensitivity of PROBSTAB

The sensitivity analysis has been used to assess the influence of five parameters and variables in slope stability. Those parameters area slope, soil depth, friction angle, bulk density and cohesion.

Figure 41 shows the result of PROBSTAB sensitivity analysis. The sensitivity analysis shows that the slope angle has the largest influence the safety factor. With decreasing of the slope angles, the safety factor increases rapidly. More over, the safety factor was decreases due to increasing slope angle.

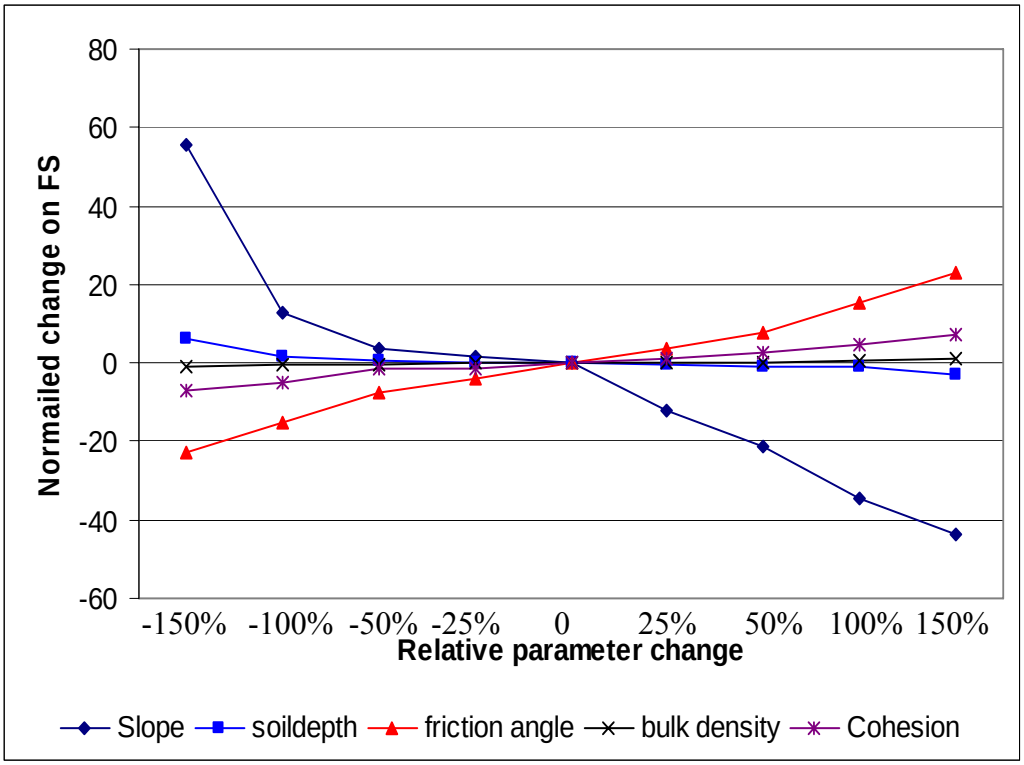


Figure 41 Sensitivity analysis of PROBSTAB script

Friction angle, cohesion and soil depth have been the next parameter which influence the slope stability. Table 15 revealed to result of PROBSTAB sensitivity analysis. In contrast with slope angle, the slope stability increases as the friction angle increases. The condition was similar to the cohesion. The safety factor increases due to cohesion increases. Or we can say that a cohesive soil was very prone to have slope stability problem. In condition of soil depth, the safety factor decreases as the soil depth increases.

Table 15 Sensitivity analysis of PROBSTAB script

Parameters	Slope	Soil depth	Phi	BD	Cohesion
	changing in %				
-150%	55.5	6.3	-22.9	-1.0	-7.3
-100%	12.7	1.7	-15.3	-0.7	-4.8
-50%	3.8	0.4	-7.6	-0.3	-1.4
-25%	1.6	0.1	-3.8	-0.2	-1.2
0%	0	0	0	0	0
25%	-11.9	-0.7	3.8	0.2	1.2
50%	-21.1	-0.8	7.6	0.3	2.4
100%	-34.4	-1	15.3	0.6	4.8
150%	-43.5	-3.1	22.9	0.9	7.3

Source: statistical analysis

7.1.3 Model Validation and Calibration

Model calibration and validation was done only for the slope stability modeling. The result of the simulated safety factor was calibrated to the actual condition from the landslide inventory maps. To test the validity of the output map, will be used the mathematical equation of equation 15.

The landslide from 1990 – 2005 based on the PGIS and field observation were used for the validation (Figure 42). Using equation 15, we can get the precision of the predicted result.
From the map, we found that:

N = 788488 pixels
N_i = 1644 pixels
M = 8851 pixels
M_i = 433 pixels

The calculated precision of the model were:

$$A = \frac{433}{1644}\sqrt[3]{\left(1 - \frac{8851 - 433}{788488 - 1644}\right)}$$
$$= 0.205$$
$$= 20.5\%$$

The results show the poor performance of the model. From the calculation, model precision was 20,5%. Poor performance of the models can be caused by:

1. poor landslide inventory map
2. poor temporal resolution for calculating the interception storage and bulk trough falls,
3. poor DEM,
4. over/under estimating by models
5. poor datasheet quality

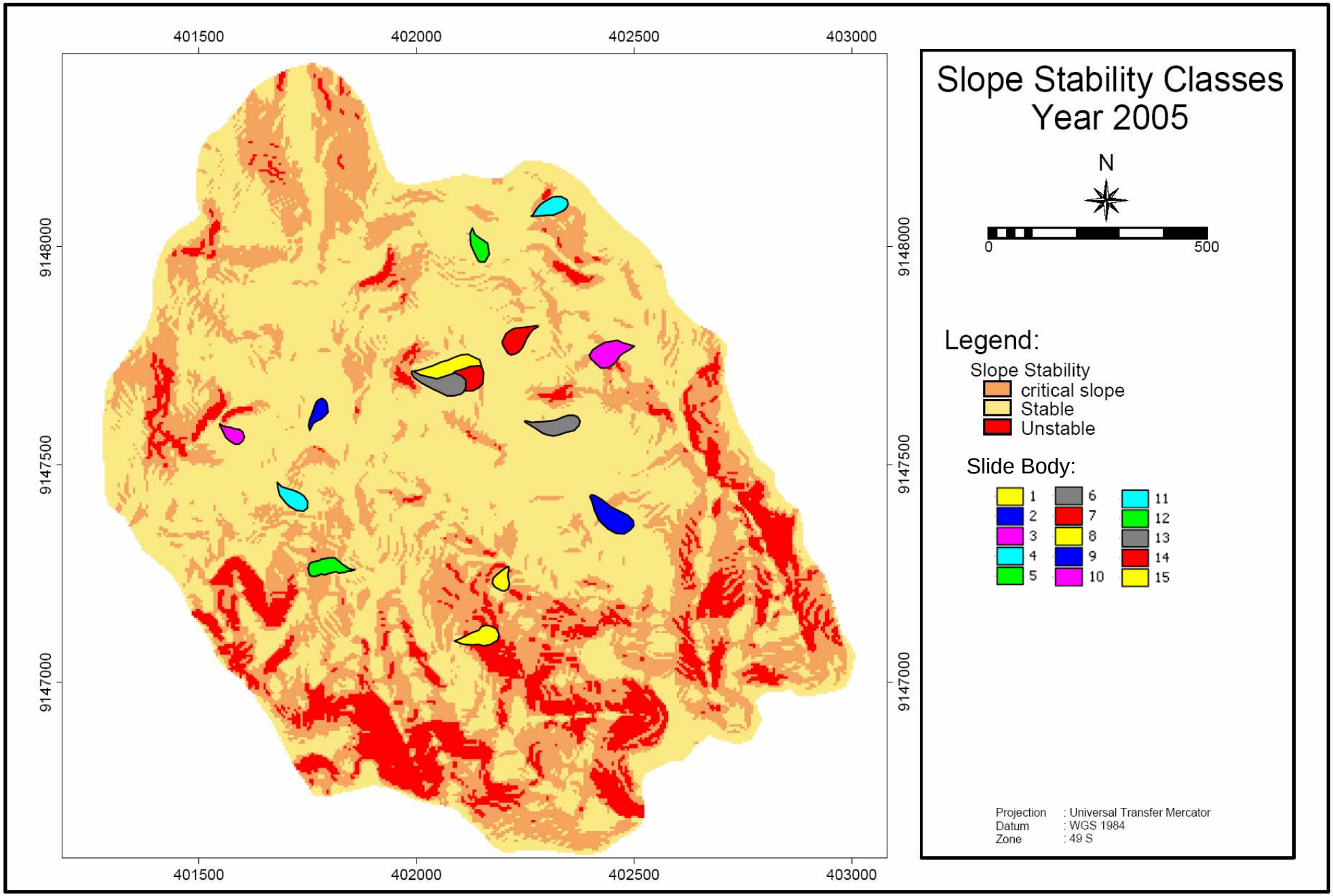


Figure 42 Slope stability classes overlaid with landslide inventory map

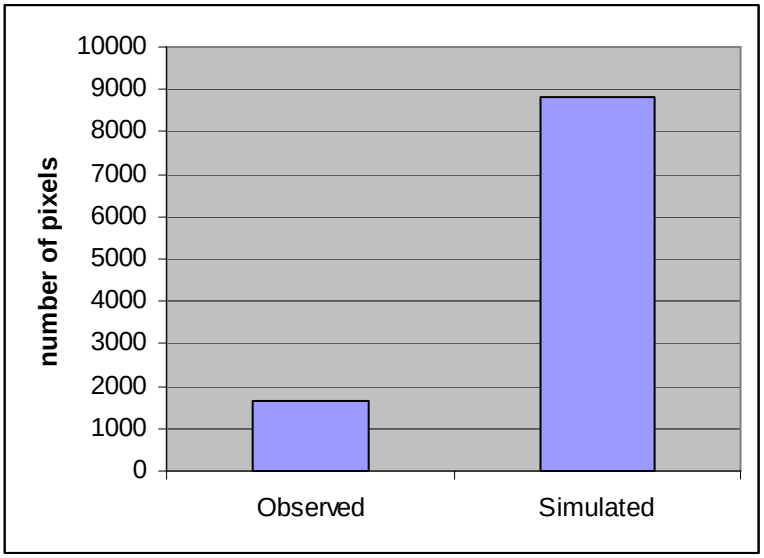


Figure 43 Simulated and observed landslide during 2005

If we compare the results of the slope stability modeling we can understand whether the model was over or under estimated. Figure 42 shows the results of slope stability modeling overlaid with landslide inventory maps. From the figure, we can see clearly that the models was over estimated in term of area and underestimated in term of location.

Overestimating can be caused by several factors (see section 7.1.3). Poor DEM was predicted as one of the causes. The DEM was detailed by field survey, but the process was done only in selected location. This condition caused the DEM resolution in general was stay the same. The other factor was poor landslide inventory data. The landslide inventory map was produce from PGIS, interview and field check. The result was landslide inventory maps which is formed as hazard. Since the other landslide which is formed as natural phenomena was avoided, the landslide inventory maps become poor. The result of this process was used as calibration. In this manner, we compare the simulated and actual condition. Therefore, the result was poor. There might be more landslides which are occur in unstable zone of simulated result, but we do not have any of those data. It is brings the result of calibration was poor.

Figure 43 shows us the comparison between observed landslides and simulated landslides during year 2005. From the chart, we can see clearly that the model was over estimating in terms of area.

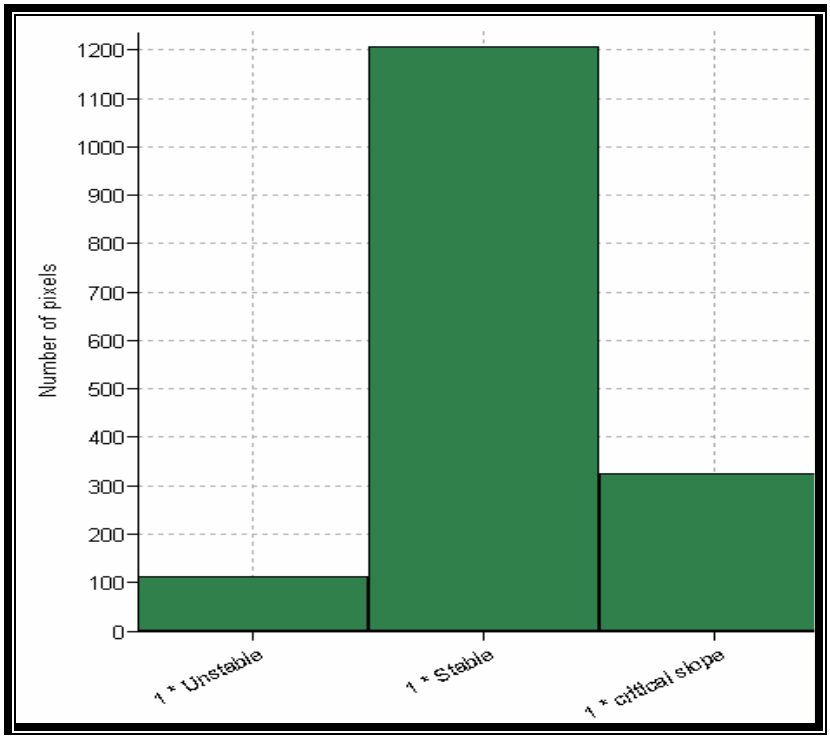


Figure 44 Distribution of observed landslide in each classes of simulated slope stability

Figure 44 shows us the distribution of observed landslides to each classes of slope stability. The result shows that most of the observed landslide was located in the stable zone, followed by critical and unstable slope. From cross map of landslide inventory map and slope stability map, we found out that 112 pixels or 2800m^2 of actual landslide was located in unstable slope, 326 pixels or 8150m^2 located in critical slope and 1206 pixels or 30150m^2 located in stable slope.

7.2 Model Evaluation

The result of the sensitivity analysis, validation and calibration has been used to evaluate the models. This chapter was dealing with models evaluation in terms of model inputs, models outputs and the modeling it self. For the modeling, we analyzed the advantage and disadvantages of the models.

The model inputs were analyzed using sensitivity analysis. The result of STARWARS sensitivity analysis was shows on figure 39.The most sensitive parameter was soil depth. The result shows the water level was changing significantly when the soil depth was varied by adding or subtracting the means value using standard deviations value. PROBSTAB sensitivity analysis brings slope as the most sensitive parameter for simulating the slope stability. The safety factor was changing significantly when the slope was changing. Figure 41 shows the sensitivity of each parameter in the slope stability modeling.

The hydrological –slope stability modeling was based on deterministic modeling. As a model, there are an advantages and disadvantages. The advantages will be:

1. Using deterministic hydrological – slope stability modeling, it is possible to assess the slope stability in term of spatial and temporal distribution.
2. By changing the input parameters, we can evaluate and create a scenario for future landslide hazard assessment. E.g. Scenario of land use change.
3. By combining hydrological and slope stability modeling, we can evaluate the difference of rainfall durations and intensity; and linked with the failure probability.

The disadvantages of the hydrological – slope stability modeling were:

1. Deterministic modeling requires high quality of data input. Time and money has to be spending to get better results. Field measurement and laboratory test has to be done. More over, data has to be collected for validation and calibration.
2. 2D or 3D analysis can not be applied.

7.3 Concluding Remarks

Validation and evaluation of the model has become an important aspect on the physical modeling. This process has been used to assess the models performance. The sensitivity of the model to changes in the parameterization can be studied by means of sensitivity analysis (Kirkby, 1993). The result of PGIS has been used to validate the result of slope stability model.

Sensitivity analysis was applied for both models, STARWARS and PROBSTAB. The result of STARWARS sensitivity analysis was shows in the figure 41. The results shows soil depth has been the most sensitive parameters for the hydrological modeling. The total storage was increases rapidly as the soil depth increases. In contrast, the storage decreases rapidly as the soil depth was deceases. The next sensitive parameters were porosity, SWRC and saturated hydraulic conductivity.

From the PROBSTAB sensitivity analysis, the most sensitive parameter was slope angle. The sensitivity analysis shows that the slope angle has clearly influence the safety factor. With decreasing the slope angles, the safety factor increases rapidly. More over, the safety factor was decreases due to increasing slope angle. The next sensitive parameter was cohesion, friction angle and soil depth. Even if the sensitivity analysis has been successfully evaluate the sensitivity of the models in many variation of input parameters, it remains questionable whether it appears the same if we applied to the different location.

Models validation has been done to assess the precision of the model. Unavailability actual water level data has made the validation and calibration for hydrological model can not be done. The only validation and calibration for this result was slope stability modeling. The result shows the slope stability models was 20.5% precise in term of area. Poor performance of the models can be caused by over or under estimating. Poor of datasheet input was considered as main causes for the poor results.

8 Conclusions and Recommendations

8.1 Conclusions

8.1.1 Conclusions from the perspective of research objectives

The objective of this research was to find out the slope stability of small catchments area using PC Raster ® simulation. To achieve that, STARWARS and PROBSTAB script has been used to assess the slope stability by means of deterministic modeling. In order to simplify the objective, specific objectives have been made. They are:

1. DEM Generation
   DEM has been one of most important input in the hydrological – slope stability modeling. The idea of using DGPS and Terrestrial Laser Scanning was good to generate a better DEM. The problem was the entire area was covered by high vegetation and the GPS satellite signal can not penetrate this area. Therefore, terrestrial laser scanning was considered as a good additional method. Again, the laser was blocked by the vegetation dense and only limited area can observe. The result of the DEM generation was quite good even tough it is quite similar with Topographic DEM.

2. Land use map
   Land use map was generated from the aerial photo interpretation in scale of 1:20.000. Lands use types of the entire sub-catchments was typical of *people forest.* In this manner, the land use type was only consisting of vegetation and housing. The result was consisting of three groups of land use type. They are settlement, secondary vegetation and primary vegetation.
   The result was validated by field check and PGIS. PGIS process was using a local language which is Java Language. The samples for PGIS were head of the village, secretary of the village, staff of the village office, the imam, on some villagers. Almost 75% of the sample was staff of the village office.

3. Sub-catchments hydrological model using STARWARS script.
   The result shows the water was fluctuate day by day. The water level increases when the rainfall happens and decreases after the rainfall. The most sensitive parameter in STARWARS was soil depth. Section 7.1.1 shows how sensitive the parameters input to the models result.

4. Perform slope stability modeling in PC Raster environment using PROBSTAB script.
   PROBSTAB is a script for calculating probability of stability. Developed by Van Beek (2002) and modified by Sekhar (2006). The most sensitive parameter was slope angle. Section 7.1.2 shows the sensitivity analysis of the PROBSTAB. Slope was recognized as the most sensitive parameter on slope stability modeling.
   The result of slope stability modeling was divided into three classes (Figure 38). They are Stable slope, critical slope and unstable slope. From the analysis, 11, 32% was unstable; 31, 86% was critical and 56, 82% was stable slope.

8.1.2 Conclusions from the perspective of research question

1. What data to perform slope stability modeling in PC Raster® environment?
   Hydrological slope stability modeling was very data demanding (see table 3). Parameter to run hydrological – slope stability model are;
   a. Soil physical properties
   b. Soil Depth
   c. Land use
   d. Soil type
   e. Geotechnical parameter
   f. Meteorological data
   g. Rainfall data
   h. DEM
   More over, the data quality was control very much to the results. The more high the quality of data input, the more height the output quality.

2. Is it possible to derive a DEM from DGPS measurement in combined with contour maps?
   DEM was one of the most important input for hydrological and slope stability modeling. GIS software was needed to generate DEM from DGPS measurement, laser scanning and contour maps. The result of DGPS measurement and laser scanning survey were elevation points. To combine with the contour maps, the contour lines need to convert into point maps. By using ArcView software, the contour maps were converted into point maps. Geoprocesing extension in ArcView was used to combine that information. The result of this process was the final point maps. The point maps were imported in ILWSI software. Kriging interpolation was applied to derive final DEM. The results was used as an input of hydrological – slope stability modeling.

3. Which other area nearby might have the slope stability problem?
   The area in the Probolo sub-catchments which has a slope stability problem was shown in the figure 37 and 38. Slope stability was divided into three classes. The area which have slope stability problem was included in the class of critical slope and unstable slope. From the analysis, 11, 32% was unstable and 31, 86% was critical.

4. Is dynamic modeling such as PC Raster® simulation relevant for providing information as an input in spatial planning in Mounts Menoreh?
   So for, the local government only used bivariate statistical model to determine the susceptibility of landslide in Mount Menoreh. Dynamic modeling using PC Raster® simulation was include more detailed parameters such as DEM, soil depth, meteorological data, land use etc. The result of these models was slope stability maps and probability of failure. These models were predicted much more detail the probability of failure in term of space an time. Therefore, it could be relevant information for spatial planning process in Menoreh Mount.

5. How to carry out sensitivity analysis to evaluate the models?
   Sensitivity analysis was applied to evaluate the model. In sensitivity analysis, the models were run in several times. Each parameter was changed in each running process and the result was used to analyze the sensitivity of each parameters. The only parameter that remains the same for each running process was rainfall. The results show that soil depth was the most sensitive parameter in hydrological modeling. Slope has become the most sensitive parameter in slope stability modeling followed by friction angle and cohesion.

6. How reliable and accurate the PC Raster® perform the slope stability assessment?
   The result of model validation shows the models was 20.5% accurate. Poor performance was caused by poor quality of landslides inventory map. The landslides inventory map was consist of hazardous landslide only. The other landslide that occurs as natural phenomena was not recorded. This condition brings the validation into biased effect. Poor temporal resolution of predicting interception storage and bulk through falls considered as one of the others causes. The interception storage was derived from NDVI. Since the available satellite imagery was only one in a year, it was assumed that the interception was the same for whole year. The other error sources were poor DEM and poor data quality.

8.2 Recommendations

Based on the conclusion of the study presented in this research, following recommendations can be given for future landslide hazard assessment project:

1. All the recent landslides which formed as hazard or natural phenomena have to be mapped in order to assess the quality of landslide hazard map.
2. Rainfall recognize as one of the main triggering factor of landslide process. Therefore monitoring of rainfall, soil moisture and ground water fluctuation were important to assess the rainfall triggered landslide.
3. The quality of datasheet is controlling the results. Good quality of datasheet will bring a good result. Therefore, all available information has to be collected and stored in to GIS.

8.3 Final Remark

The conclusion and recommendation presented in this chapter were based on research study in tropical area of Indonesia. The research was done in a sub-catchments area with limited data and poor resolution (spatial and temporal). Therefore the results and conclusion should not be treated as too general. It is possible that similar studies in area with different location, a better datasheet and better resolutions will end up with a different results and conclusions.

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Appendix 1

List of Symbol

α : Air entry value

β : Angle of topography slope

c : Soil Cohesion

Φ : Friction Angle

γ_w : Unit Weight of Water

γ : Unit Weight of Soil

θ : Actual volumetric soil moisture content

FS : Factor Safety

Ksat : Hydraulic Saturated Conductivity

Pr : Percolation

Q : Groundwater flow

x : X coordinate

y : Y coordinate

z : Depth of the soil/ Elevation point

u : Pore Water Pressure

Appendix 2

Soil Depth

ID	X	Y	S_DEPTH
1	401701.378	9146882.416	3.20
2	401751.482	9146970.834	1.30
3	401816.322	9147062.199	1.40
4	401895.898	9147177.143	1.10
5	401884.109	9147292.086	0.95
6	401842.847	9147436.503	1.30
7	401813.375	9147519.026	0.85
8	401739.693	9147572.077	0.75
9	401692.536	9147678.179	0.90
10	401713.167	9147793.122	0.85
11	401701.378	9147884.488	0.78
12	401733.798	9147955.222	1.20
13	401775.060	9148058.377	0.78
14	401766.218	9148173.320	2.10
15	401748.535	9148267.633	1.70
16	401751.482	9148373.735	2.10
17	401548.120	9147132.934	2.30
18	401521.595	9147218.405	2.30
19	401559.909	9147289.139	3.20
20	401604.118	9147368.715	0.85
21	401654.222	9147439.450	0.98
22	401719.062	9147536.710	1.20
23	401515.700	9147386.399	0.75
24	401630.644	9147262.614	0.85
25	402308.516	9146746.841	1.40
26	402234.834	9146849.996	1.30
27	402122.838	9146944.308	1.30
28	402055.051	9147017.990	1.30
29	402004.947	9147115.250	1.40
30	401966.633	9147212.510	1.10
31	402264.307	9146911.888	1.20
32	402391.040	9146914.836	1.20
33	402205.362	9147292.086	1.50
34	402113.996	9147359.874	1.40
35	402037.367	9147418.819	1.25
36	401946.002	9147460.081	1.61
37	401807.480	9147772.492	0.88
38	401848.742	9147616.286	0.94
39	402007.895	9147586.813	1.20
40	402087.471	9147575.024	1.40
41	402205.362	9147510.184	1.55
42	402311.463	9147468.923	1.30
43	402352.725	9147395.241	1.70

ID	X	Y	S_DEPTH
44	402426.407	9147247.877	1.40
45	402293.780	9147737.124	2.10
46	402287.885	9147834.384	1.20
47	402252.518	9147902.171	0.90
48	402220.098	9147975.853	0.85
49	402134.627	9148046.588	2.40
50	401993.158	9148034.799	1.90
51	401913.582	9147978.801	2.60
52	401836.953	9147908.066	0.88
53	402305.569	9147996.484	0.80
54	402376.303	9147949.328	1.90
55	402444.091	9147940.486	1.80
56	402497.142	9147863.857	1.94
57	402532.509	9147778.386	1.10
58	402579.665	9147660.495	1.06
59	402617.980	9147577.972	1.12
60	402665.136	9147486.606	1.70
61	402679.872	9147395.241	2.10
62	402662.189	9147318.612	1.30
63	402653.347	9147250.825	1.20
64	402644.505	9147162.406	2.10
65	402653.347	9147056.305	2.60
66	402700.503	9146973.781	1.50
67	402753.554	9147395.241	2.10
68	402797.763	9147295.034	3.40
69	402830.183	9147244.930	1.70
70	402821.341	9147165.354	1.30
71	401536.331	9147592.708	3.04
72	401610.013	9147642.812	0.85
73	401521.595	9147952.275	0.70
74	401639.486	9147934.591	0.87
75	401618.855	9148208.688	3.05
76	401960.738	9147793.122	2.70
77	401468.544	9147713.546	1.90
78	401831.058	9147359.874	2.10
79	401772.113	9147353.979	3.20
80	402184.731	9147079.883	3.05
81	402146.416	9147834.384	3.80
82	401769.166	9147162.406	2.60
83	401459.702	9147460.081	2.40
84	401515.700	9147796.070	3.05
85	401836.953	9146864.732	3.05
86	402063.893	9146864.732	3.05
87	401427.282	9147368.715	0.85
88	401545.173	9147454.186	3.20

ID	X	Y	S_DEPTH
89	401663.064	9147516.079	3.20
90	401834.006	9147575.024	3.40
91	401910.635	9147716.493	3.10
92	402055.051	9147793.122	3.50
93	402167.047	9147692.915	3.50
94	402293.780	9147631.023	3.51
95	402432.302	9147622.181	2.87
96	402497.142	9147445.344	3.40
97	402505.983	9147353.979	2.40
98	402500.089	9147253.772	2.20
99	402556.087	9147127.039	2.50
100	402523.667	9147032.726	3.50
101	402591.454	9146923.677	2.50
102	401374.231	9147477.764	3.25
103	401403.704	9147633.970	3.50
104	401377.178	9147751.861	2.20
105	402373.356	9147899.224	3.40
106	402505.983	9147975.853	3.50
107	401574.646	9147940.486	0.85
108	402146.416	9146779.261	2.02

Appendix 3

Soil Physical properties

No	Sample	X_COORD	Y_COORD	Ksat (m/day)	ThetaSat [m3/m3]	alpha [-]	gamma [kN/m3]	C [kPa]	phi [°]
1	1	401760.10	9147943.91	0.43	0.5262	9.35	14.21	71	32.5
2	2	401682.77	9147540.46	0.57	0.5009	9.35	14.504	71	31.8
3	3	401474.32	9147419.43	0.55	0.5269	9.35	13.524	92	28.5
4	4	401793.72	9147587.53	0.65	0.5373	10.1	14.602	48	34.6
5	5	402123.20	9147863.22	0.78	0.4836	10.1	14.308	99	19.4
6	6	402136.65	9147977.53	0.56	0.4778	10.1	15.386	10	18.2
7	7	401672.69	9146982.35	0.97	0.5073	9.56	16.464	85	27.5
8	8	402351.83	9147150.46	0.87	0.507	9.56	15.386	43	31.3
9	9	402617.43	9146820.97	0.83	0.4832	9.56	14.896	87	26.4
10	10	402637.60	9147503.48	0.52	0.4504	9.26	13.328	67	19.1
11	11	401763.46	9147274.86	0.48	0.4703	9.26	14.21	43	22.4
12	12	402439.24	9147547.18	0.75	0.4838	9.26	13.23	75	21.6

Appendix 4