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Contributed Paper

Landslide Susceptibility Mapping: Effect of Spatial Resolution towards the Prediction of Landslide Prone Area in a Tropical Catchment

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Abstract

Landslide has become a common problem especially in tropical countries such as in Malaysia. This study was carried out in Fraser Hill Catchment using a GIS based deterministic slope stability analysis model, that combine infinite slope stability and steady state hydrology assumptions to quantify the stability called SINMAP. The model requires some inputs. Historical landslide inventory for the catchment were obtained from interpretation of multispectral SPOT 5 image and Global Positioning Survey (GPS) survey. Topographic maps at scale of 1:50,000 were used to construct Digital Elevation Model (DEM). Soil strength parameters and hydrologic parameters were gathered from *in situ* test as well as previous records. The purposes of this study were to map the landslide susceptibility of Fraser Hill Catchment and to test the usage of different DEM spatial resolution towards the accuracy of the model. Landslide susceptibility map for the study area was produced as the output of this model. The result will be compared with the actual location of slope failure that occur within the catchment to assess the model performance. Results showed that, for this catchment, SINMAP gives good results in predicting the landslide with 68% of the current landslide inventory fall within unstable class as their calculation of Stability Index (SI) are less than 1. Results from the spatial resolution analysis showed that 20 and 30 meter resolution gave optimum result compared to others.

Keywords: shallow landslide, landslide susceptibility map, geographic information System (GIS), digital elevation model (DEM), spatial resolution

1. INTRODUCTION

Landslide has been acknowledged as one of natural disasters that occur all over the world. Every year, landslides are responsible for loss of several human lives and several million dollars of damage to public and private property [1, 2]. Shallow landslide is one of the most common types of landslide that often occurs in different climatic region [3-8]. Shallow landslide can be defined as soil slips that often develop on steep slope and their depths are generally not more than 1-2 m [37]. These landslides can involve different soils whose mechanical characteristics vary significantly with differences in water content, sediment size and sorting [9]. The dangerousness of shallow landslide is it can transform into debris flow that flow rapidly down hillslopes or stream channels triggered by intense rainfall. This phenomenon is dangerous due to their rapid kinematic evolution and large areal diffusion [8]. Shallow landsliding can generate debris flows that scour low-order channels, deposit large quantities of sediment in higher order channels and pose a significant hazard [4, 5]. Normally, shallow landslides occurred during rainstorm [10-13] or during the rapid snow melt [5]. Both of the shallow landslide triggering factors will reduce the shear strength caused by increase of pore-water pressure [14].

In tropical country, the landside incidences often occur during monsoon season where precipitation during that time is heavier and intense compared to other period. Climatic conditions in tropical area are the main factor responsible for slope stability or landslides that occur in hilly areas [10, 15]. Malaysia is one of tropical countries that facing landslide problem. One way to minimize the after effect of landslide occurrence is by delineating the potential area through producing a landslide susceptible area map. By doing this, developers and planners are well informed regarding the spatial location of potential slide area. Therefore, any development on the potential slide area can be avoided and safety measures will be implemented. Back in the old days, landslide susceptibility map was produced by geologists or landslide experts using manual *in situ* interpretation based on their experience. Then, they will draw a landslide susceptibility map based on their observation over the specific area.

Nowadays, with the advance of technology and computer performance, landslide susceptibility maps are produced by using much kind of digital data that being process and manipulated by using geographic information system (GIS). GIS has been used in wide range of environmental studies such as in meteorological [35, 36], hydrological [23, 25], land use land cover change [3] and geological studies [4, 7]. By using GIS, the extent of the study area can be on catchment wide basis. One of digital data that important to study landslide is elevation data or digital elevation model (DEM). The main input of most of the study is using Digital Elevation Model (DEM) to represents the topographic area in digital representative [16]. Topographic form is a fundamental element in any geomorphologic analysis for landslide identification [17-19]. As topographic was found out to be the important factor that govern the landslide occurrence [9, 20, 21], it is important to use higher quality DEM to represent the topographic surface. One of important aspect of the DEM is the spatial resolution or the size of the DEM pixel. Thus, there is a need to study the effect of the spatial resolution towards a grid-based modeling. In this the study, the objective is to produce a landslide susceptibility map for Fraser Hill catchment and to determine the effect of spatial resolution towards the landslide susceptibility map produced by the model.

STUDY AREA

Fraser's Hill catchment is situated in Pahang and it is one of the popular highland resorts in Malaysia. The size of the catchment is 9 km^2 and the main river is Teras River (Sg. Teras). The original geomorphology of the Fraser Hill catchment characterized by hilly terrain and most of the natural slopes are steep with more than 50° [22]. The relief of the catchment ranges from 400 to 1300 m above mean sea level. Since it is situated in high area, Fraser Hill catchment receives more rain compared to other areas and due to the long saturation, the strength of slope might gradually decreasing. The mean annual rainfall is about 2624 mm with average of 208 rainy days in a year [23]. Fraser Hill catchment is underlain by granitic rock as its parent body which is composed of clayey sand or sandy clay that has moderate friction angles and cohesion values. Base on the geological map, the catchment and its surrounding is mainly composed by Main Range Granite. The Fraser Hill catchment is located at the tropical climate area which experienced hot and wet season throughout the year. [24] had previously study the climatology characteristic of Fraser Hill. Based on their study, the day temperature ranges between 19.5 °C to 25 °C, the relative humidity ranged from 65% to 100% and the sky brightness ranges from 20% to 100%. The rainfall distribution in Fraser Hill area is highly influenced by major air-steam across Peninsular Malaysia that annually, produced four seasons which are northeast monsoon from November or early December through March, first inter-monsoon from April to May, southwest monsoon from May through September or early October and second inter-monsoon from October to early November [25]. A meteorological station located at Bukit Peninjau, Fraser Hill recorded an annual mean rainfall of 2624 mm with an average of 208 rain-days throughout the year [25]. Periods around October till November found out to be the wettest period with relative humidity valued at 90% throughout the year [25]. Figure 1 shows the location of Fraser Hill within Peninsular Malaysia and figure 2 shows the topographic of Fraser Hill catchment.

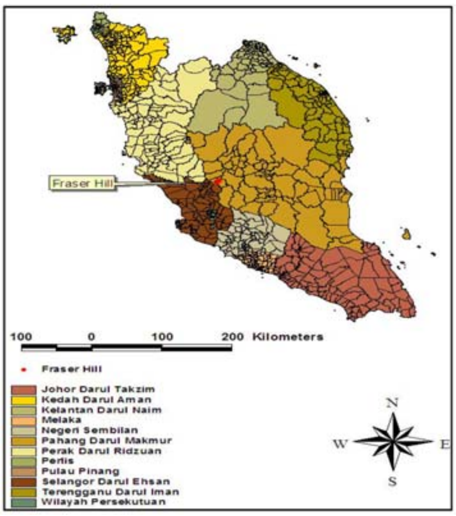

Figure 1. Location of the Fraser Hill Catchment in Peninsular Malaysia.

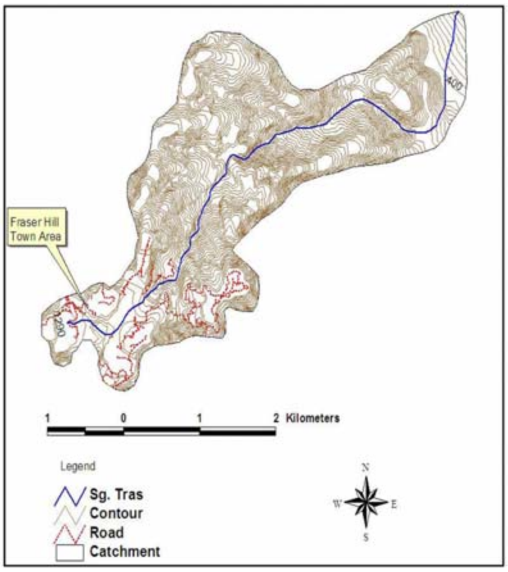

Figure 2. Topography of Fraser Hill catchment.

2. MATERIALS AND METHODS

This study compromised of several sections in methodology phase. Input required to run the model are such as soil bulk density, hydraulic conductivity, soil cohesion and friction angle and soil depth. To calibrate and validate the model, a historical landslide inventory data are required. All the soil sampling location and the landslide location were recorded using a hand held GPS.

2.1 Geotechnical Input

Altogether, 18 soil samples were measured. In this study, *in situ* sampling was done using core soil sampler and hand auger to collect soil samples at several locations of undisturbed area within the catchment. All of the samples were measured and analyzed in lab to find the final value of each parameter. In geotechnical input data, there are four parameters that taken into consideration which are soil bulk density, soil cohesion, soil friction angle and also the depth of the soil. Soil bulk density was calculated using equation 1. In this model, the mean value used to run the model is 1895 kg/m^3.

$$\text{Wet bulk density, } \rho_s = \frac{(\text{(weight of ring+wet core)-(weight of ring)})}{\text{Volume of sample ring}} \tag{1}$$

Soil depth was estimated using an electrical resistivity survey. In this study, the depth of the soil estimated using soil depth value from four locations within the catchment that represent lower and upper catchment of the Fraser Hill. In this model, the input of the soil depth is in form of a mean single value that will represent the entire catchment soil depth. Value of 2.65 meter of soil depth was used in this study. For this study, a value of 2.65 meter soil depth adapted for all model running came from the interpret of the resistivity result. The example of the soil depth estimation is as shown in Figure 3 which reflected the result of resistivity measurement downstream of the catchment.

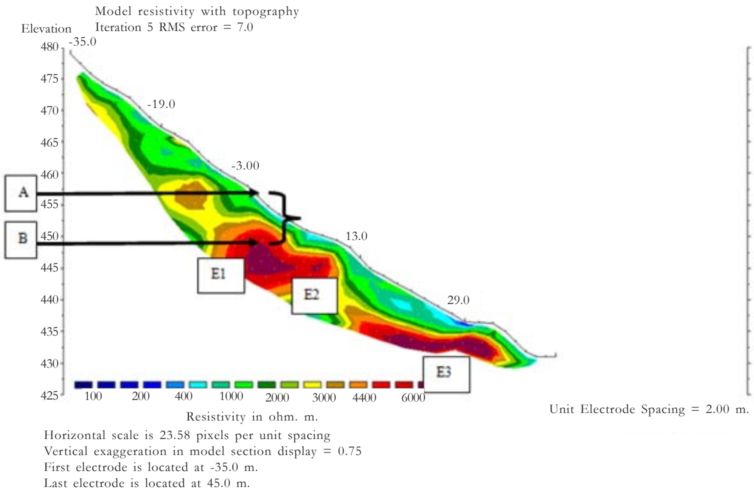

Figure 3. Method to estimate soil depths from resistivity survey.

According to [38], the variation of resistivity value for granite rock is in the range of 5 × 103 - 106. From Figure 3, there were three clear anomalies (E1, E2 and E3) in the centre of the image. That might indicate a fresh granite rock. Since the parent rock of Fraser hill catchment is from granitic rock [39], it was assumed that the soil depth definition is from the top soil to the surface of a granitic rock as shown Figure 3. Figure 3 shows that there was three location of granitic rock within the selected site. To get the estimation of soil depth, the difference between elevations of the perpendicular depth of the first intact surface (E1) of the fresh granite which represent as B is deducted from the top soil surface (represented as A) is calculated. For example in Figure 3, elevation at B (456.25 m) minus elevation at A (446.25 m) which resulted 7.5 m of soil depth. The same procedure also applied to E2 and E3. Then, the result of soil depth from E1, E2 and E3 were averaged.

Soil cohesion and soil friction angle are basically the indicator that shows how strong are the soil particles stick to each other. Both of the parameter was analyzed using a digital direct shear box machine. In this model, both parameters were used as a range value input. For soil friction angles, the value was in the range of 14.85° to 42.76° while cohesion ranged from 5.28 kPa - 30.00 kPa respectively.

2.2 Hydrological Input

Hydrological input required in this model was in term of wetness index (T/R), ratio of transmissivity (T) (m^2/hr) of the soil and rainfall recharge into the soil (R). T is the transmissivity or the vertical integral of the hydraulic conductivity of soil and can be determined by:

$$T = k_s \times h \tag{2}$$

where k_s is the hydraulic conductivity of the soils determined in the lab using permeameter while h is the thickness of the saturated soil above the failure surface. k_s was determined using constant head method as suggested by [26]. Using this method the value used in this model is 0.19 and 2.46 m hr^{-1} respectively. These hydraulic conductivity values were then multiplied by the thickness of saturated soil depth (h). The h value was estimated through resistivity survey at two sites within the catchment. From the soil depth estimation, it was assumed that the *h* value is at assumed to be constant 2.65 meters depths for all over the catchment area (based on average electric resistivity survey). R is the steady state recharge. However, in this study, there was a limitation because of lack of data on the evaporation and infiltration rate. Therefore the R is assumed to be as the event rainfall itself as also done in previous study [7,15]

In this study, we adopt a storm event from Department of Drainage and Irrigation of Malaysia (DID).

Table 1. Risk of landslide in hilly terrain based on daily cumulative rainfall.

Risk of Landslide	Daily Cumulative Rainfall (mm)
No	< 30
Low	30 to 60
Medium	61 to 100
High	>100

(Adapted from http://infobanjir2.water.gov.my/explain.htm)

2.3 The Model

This study applied a slope stability model called Stability Index Mapping or SINMAP to produce the shallow landslide susceptibility area within the Fraser Hill catchment. The model coupled both geotechnical and hydrological and was developed by [27]. The model compromises of three major components which are modified as infinite slope equation, topographic wetness index and stability index. [27] has corporated the above three components into a simplified final form of SINMAP model equation which describes the stability index equation as:

$$FS = \frac{c + cos\theta[1 - min\,(\frac{R}{T}\frac{a}{sin\theta},1)r\,]tan\varnothing}{sin\theta} \quad (3)$$

where the variables a is specific catchment area and θ represent the slope. Both of the variables derived from catchment topographic determined using DEM. Other parameters such as C (cohesion), ∅ (soil friction angle), R/T (recharge over transmissivity), and r (the ratio of water to soil density) which were obtained from laboratory analysis are manually entered into this model. Since these parameters are varied in field condition and considered more uncertain, they are specified in terms of upper and lower boundary values [27].

For each cell of the catchment DEM, SINMAP calculates a factor of safety (FS), which is defined as the ratio between resisting force and driving force toward a landslide occurrence. This is a dimensionless index number with a value between above zero and 10. If the index falls below one, there is a high probability that the area is unstable whereas high index values (greater than one) indicate better stability [28]. Table 1 shows the stability index classes together with brief explanation on each hazard class [28]. Based on table 2, three classes were defined as naturally unstable by the model which is lower threshold, upper threshold and defended slope zone as their factor of safety calculation resulted of value less than 1.

Table 2. Stability index class defined by the model.

Condition	Class	Predicted State
SI > 1.5	1	Stable slope zone
1.5 > SI > 1.25	2	Moderately stable zone
1.25 > SI > 1.0	3	Quasi-stable slope zone
1.0 > SI > 0.5	4	Lower threshold slope zone
0.5 > SI > 0.0	5	Upper threshold slope zone
0.0 > SI	6	Defended slope zone

* SI is defined as Stability Index

However, to simplify the classification, this study only categorized the result into 2 classes which are FS<1 consists of Defended and Upper and Lower threshold which means there were possibilities of landslide occurrence (unstable area) and FS>1 consists of Quasi-stable, Moderately stable and Stable which means there were possibilities that the area is safe from landslide occurrence (stable area).

3. Result and Discussion

The model accuracy relied heavily on the parameter input as stated in previous study using this SINMAP model [7, 21, 26, 29]. Results of the parameter input used in this study are shown in Table 3.

Table 3. Geotechnical and hydrological parameters used in the study.

Parameter	n	Mean	Range	SD(±)
Bulk Density, kg m^{-3}	18	1895	1493 - 2267	214.9
Internal Soil Friction Angle, °	18	34.22	14.85 - 42.76	6.52
Cohesion, kPa	14	15.87	5.28 - 30.00	10.6
Hydraulic Conductivity, m hr^{-1}	17	2.06	0.19 - 2.46	0.61
Soil Depth, m	2	2.65	1.05 - 4.23	2.25

In this landslide model, soil bulk density input is in the form of mean value. The mean value of soil bulk density for Fraser Hill catchment is 1895 kg m^{-3}. The minimum and maximum value of soil bulk density value is 1493 kg m^{-3} and 2267 kg m^{-3} respectively with SD of ±214.9. Previous study in Fraser Hill area also gave almost identical result with this study. [34] Stated that the bulk density value for Fraser Hill is between 1600 to 2150 kg m^{-3} while [22] stated that mean value of bulk density in their landslide site was 1980 kg m^{-3}. For hydraulic conductivity, the input to the model is in the form of lower (minimum value) and upper (maximum value). From the laboratory analysis, the minimum and maximum value for hydraulic conductivity for Fraser Hill is 0.19 and 2.46 m hr^{-1} respectively. The mean value of hydraulic conductivity for Fraser Hill catchment is 0.81 m hr^{-1} while the SD is ±0.61 m hr^{-1}. There was a wide range of permeability in the soil within Fraser Hill catchment. The results from the hydraulic conductivity also showed that the soil at the lower part of the catchment is more permeable compared to sampling location at the upper catchment. In addition, from the preliminary sieve analysis, the soil in the downstream of Fraser Hill catchment was found out to contain more percentage of silt and sand compared to the soil in upstream part of the catchment. Soil friction angle and cohesion also imputed in the model as lower (minimum value) and upper (maximum value) input. For soil friction angle, the value was in the range of 14.85° to 42.76° while cohesion ranged from 5.28 kPa - 30.00 kPa respectively. In a study done by [22], the range of soil friction angle in Fraser Hill is between 27° - 42°. Meanwhile, previous study by [22] on the soil cohesion for Fraser Hill area ranges between 6 kPa to 27 kPa. Soil depth also functions as an input in SINMAP model but in the form of mean value. For this study, a value of 2.65 m soil depth adapted for all model running from the interpretation of the resistivity survey.

3.1 Landslide Susceptibility Area

The SINMAP model produced the SI map as the main output. The SI map is the reflection of Factor of Safety (FS) calculation which used to classify the terrain stability for each grid cell of the study area. Besides SI map, SINMAP also produced several GIS theme such as contributing area, saturation zone area, slope, flow direction, pit filled DEM and calibration region. Slopes, flow direction, pit filled DEM and calibration region were all analyzed during the DEM processing phase. These GIS themes generated in the model are used as the topographic input to predicted possible landslide prone areas.

Figure 4 shows the landslide susceptibility map for Fraser Hill. Stability Index value ranged between 0 (most unstable) and 1 (least unstable). Small black dot in the figure represent the location of the actual shallow landslide in the catchment. Based on the stability index map for Fraser Hill, the naturally unstable area (lower threshold, upper threshold and defended) covered almost 68% of the catchment area while the remaining covered the naturally stable area (stable, moderately stable and quasi-stable). Naturally unstable area is clarified as area which has the FS calculation less than 1 (FS<1) while naturally stable is the area that FS calculation more than 1 (FS>1). The location of the stable area mostly covered at the upper such as at Fraser Hill town area and lower part of the catchment such as at Tranum town.

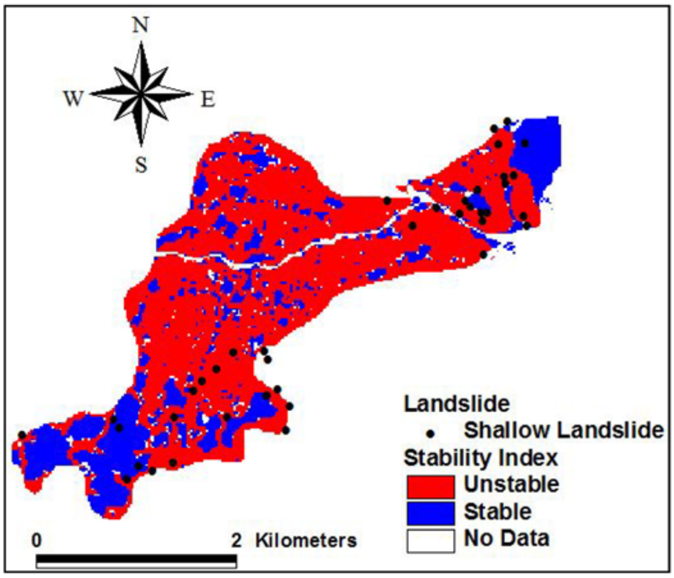

Figure 4. Stability index (SI) map for Fraser Hill catchment.

Based on total of 39 shallow landslide inventories used in this analysis, it was found out that the landslide susceptibility map predicted by the model was able to identify 80% of historical shallow landslides (31 out of 39 shallow landslides). Among 31 detected landslide, 21 landslides fall into unstable area while the rest fall into the stable (7 landslides), moderately stable (1) and quasi-stable (2) class, respectively.

3.2 Spatial Resolution Effect on Landslide Susceptibility Mapping

This study used a contour map at scale of 1:50,000 as the input that represents topography to generate DEM. Since the main input of this study is the topography itself that being represented using DEM, so, determining the best spatial resolution for DEM is important for the whole study [30]. To determine the effect of DEM spatial resolution for landslide susceptibility in Fraser Hill catchment, 20 m, 30 m, 40 m, 60 m and 80 m DEMs were aggregated in ArcView GIS from the same topographic map scale source respectively. To explore the DEM spatial resolution effect on the accuracy of the produced susceptibility map, total landslide that can be captured from each DEM resolution was used as an indicator. Furthermore, during the time of this analysis, all of the soil and hydrology parameter input were put constant for all DEM size. Input of parameter during this analysis was shown in table 4.

Table 4. Summary of parameter inputs used for the analysis are shown below. Soil density is in *kg/m³*, *T/R* in *m*, cohesion in *kPa* and soil friction angle in °.

DEM Spatial Resolution	Soil Density	T/R max	T/R min	Cohesion max	Cohesion min	*Φ* Max	*Φ* Min
20m	1895	88.353	6.882	0.66	0.11	42.76	14.85
30m	1895	88.353	6.882	0.66	0.11	42.76	14.85
40m	1895	88.353	6.882	0.66	0.11	42.76	14.85
60m	1895	88.353	6.882	0.66	0.11	42.76	14.85
80m	1895	88.353	6.882	0.66	0.11	42.76	14.85

To explore how different DEM resolution influence relative shallow landslide susceptibility, the behavior of two model output was derived from the DEM and used in the susceptibility assessment. Specific catchment area constitutes the topographic characterization while Stability Index map constitutes the areas prone to landslide predicted by the model. The representation of topographic in terms of DEM may not able to capture the real world but it is a noble attempt to view the real world for further analysis. However, issues regarding which spatial resolution of DEM must be used in certain need to be studied. As stated before, to explore the changes of DEM spatial resolution towards the shallow landslide modeling, it was manipulated using range of DEM size (20 m, 30 m, 40 m, 60 m, and 80 m).

The effect of the resolution size evaluated in term of stability index (SI) map produced using difference DEM size. The unstable area which defined as SI value < 1 was located under Lower Threshold, Upper Threshold and Upper class. These specific classes will be used as the "judgment factor" that will assess the effect of DEM spatial resolution changes towards the landslide modeling process. Table 5 shows the changes of catchment size towards the manipulation of DEM resolution.

Table 5. Effects of DEM spatial resolution manipulated towards stable and unstable area.

Resolution (m)	Stable	Unstable	Total Area (km^2)
20	2.3	5.5	7.8
30	2.1	5.2	7.3
40	1.7	4.6	6.3
60	1.4	3.8	5.2
80	0.8	2.6	3.4

By increasing the DEM resolution size, the captured total catchment area was reduced. Using 20 m and 30 m DEM, the size of the catchment is 7.8 and 7.3 km^2 respectively. However using coarser DEM size made the captured catchment area became lesser. For instance, the model can only captured 3.4 km^2 of the total catchment size when using a 80 m DEM. There was a very significant change of total catchment area between using 20 m and 30 m DEM. This condition suspected to 'physical appearance' of the DEM itself represented by a square box which made it unable to capture the actual size of any polygon especially on the edge of an area or at the border side of certain polygon. Even if any user used 1 meter × 1 meter size of DEM, it might not be able to solve the problem because of the physical appearance of the DEM.

Besides that, coarser DEM also shows a decrease in identifying the unstable area (FS<1). 20 m DEM gave the model to identify 5.5 km^2 of the catchment area to be in unstable area while 30 and 40 m size gave the model to pick out 5.1 and 4.6 km^2 of the catchment area as unstable area. 80 m DEM which represent the coarser resolution in this analysis only able to identify 2.6 km^2 of the catchment as unstable area. However, the model gave a consistent result when the percentage of unstable area for each DEM size taken into consideration. 20 m, 30 m, 40 m, 60 m and 80 m DEM were all gave quite similar percentage ranging from 70.5% to 76.5%. Figure 5 shows the effects on Stability Index grid based on DEM size manipulation. The square box was captured at the same location for all DEM resolution. Noted that, the coarser DEM used in Figure 5, the more 'white area' which have no value appear. The area classified as "NO DATA" in SINMAP model. Therefore, from the analysis, it can be concluded that the optimum resolution to map the landslide susceptibility area in Fraser Hill catchment using a 1:50,000 contour map with 20 m contour interval is 20 m to 30 m resolution. Previous study by [31] in Baum, Korea resulted that 5 m, 10 m and 30 m DEM resolution showed similar value (where the normalized area values 0.97, 1.00 and 0.92, respectively) while 100 m and 200 m DEM gave the lowest result. In conclusion, at least 30 m DEM size must be used in any landslide susceptibility study in Korea. A study in a small basin in the Northeastern region of Italy found out that, DEM generated using LiDAR will gradually losing its spatial representation of the topographic if the DEM was set to 10 m resolution [32]. Finding the perfect DEM resolution might not be able to be done as it is because no resolution can possibly represent the dimensions of all different slope failures scattered in space and time [33].

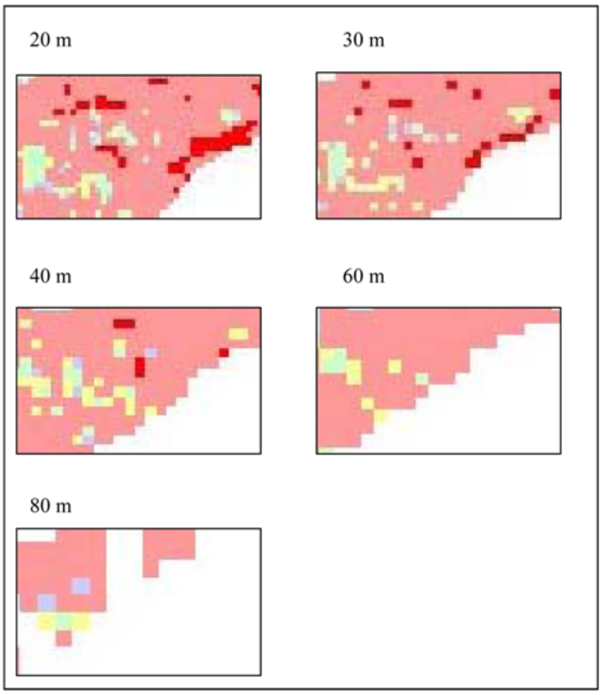

Figure 5. DEM spatial resolution effect on Stability Index grid according to spatial resolution size.

4. CONCLUSION

A landslide study has been done in Fraser Hill catchment to determine the potential shallow landslide prone area in the catchment. Based on the landslide susceptibility map, it was clear that Fraser Hill catchment is quite susceptible to landslide particularly shallow landslide where 68% of the catchment area predicted to be in naturally unstable zone. Historical landslide inventory collected to evaluate the model. Total of 39 shallow landslide locations are gathered. Out of the 39 landslide inventory, the landslide susceptibility map produced by SINMAP was able to identify 80% of it (31 out of 39 shallow landslides). However, among those 31 landslides, only 21 landslides fall into the unstable area while the rest fall into stable area. Most of the unstable zone located at centre part of the catchment where majority of the area covered with natural dipterocarp forest especially where the slopes area steep. However, there were some areas in the lower catchment (in the vicinity of Tranum Forest Reserve) predicted to be unstable. Stable areas, which covered only 32% of the catchment area, are mostly located at the Fraser Hill town area and at Tranum town. However, although the town area considered being in stable area, it might happen that the area also can experience landslide as the cause of extreme rainfall events and major human development. Uncontrolled developments on the slope area in the town area can also contribute to the landslide occurrence.

Spatial resolution of any study is important as it affects the spatial extent and spatial accuracy of the output. In a landslide study, this issue cannot be taken lightly as it will affect the landslide susceptibility or landslide hazard mapping produced. In this study, the effect of spatial resolution on the accuracy of landslide susceptibility mapping was evaluated. 1:50,000 topographic map aggregated into 20 m, 30 m, 40 m, 60 m and 80 m of DEM spatial resolution in GIS to determine the effects of DEM resolution effect on the SI map output. Result shows that coarser DEM resolution causes the model to detect less of the catchment area and thus affect the predicted unstable area in the catchment. In conclusion, for studying shallow landslide over a longer timeframe, the 'perfect' DEM resolution may not exist because no resolution can possibly represent the dimensions of all different slope failures scattered in space and time. However, the best way to solve this issues the choice of whatever DEM resolution might depend on the availability of height data source and the spatial accuracy required for any specific study.

Shallow landslides and other forms of landslide are difficult to predict because there are various factors that should be taken care of into calculation. Another problem with landslide prediction is the spatial location and spatial extent of the landslide predicted to be occurred. However, results from this study suggest that the predicted unstable areas might not suitable for any land development without safety and engineering precaution. Finally, there are limitations inherent in slope-stability maps. The landslide map that is produced by the SINMAP model is a probability map rather than an actual landslide hazard map. Experts may have different views on this kind of map and as such there are different ways to interpret the map. To environmental planners the slope-stability map may be good enough for general planning purposes such as for environmental impact assessment studies and land use zoning where the map can be viewed as presenting areas of safe development and areas that needs further investigation. In Malaysia, the environmental impact assessment report is required for specific development projects. Many proposed projects may be located within or nearby environmentally sensitive areas such as water catchments and hilly topographic where problems of landslides may occur and affect the sensitive areas. In this aspect the map may serve the purpose as it is able to locate the landslide susceptibility area within an area. Field engineers may argue about the accuracy of the map on-site. It is impossible to evaluate accurately the stability of individual slopes without detailed engineering field analysis.

In the future, it is recommended that further soil and hydrology exploration should be done for each susceptibility class (Defended, Upper threshold, Lower threshold, Quasi stable, Moderately stable and Stable) provide by this model for both unsaturated and in saturated environment. This might give more precise information on how good the model is in predicting landslide susceptibility area. As topography is a controlling factor in this model, it was suggested that in future, better height source should be used to generated the DEM rather than interpolate it from topographic map at scale of 1:50,000. LiDAR or any other data that have higher precision should be used to get more accurate information on topography representation.

Besides that, rather than using deterministic model such as SINMAP, future study might also try to use other method to map the landslide susceptibility such as statistical, heuristic or morphological mapping method. If deterministic and probabilistic approach such as SINMAP much more preferred, future studies also can used other GIS-based landslide modeling such as Shallow Lansliding Stability Model (SHALSTAB), Level 1 Stability Analysis (LISA) and Weight of Evidence (ArcWofE).

This study has been applied to a small catchment (< 10 km^2) in hilly tropical rain forests. It would be interesting to apply the SINMAP or any other landslide modeling method in other areas.

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