Landslide Hazard Zonation in Sri Lanka: An Assessment of Manual and GIS Based Automated Procedure in Preparation of Geology Weight Map

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Many techniques have been proposed for landslide hazard zonation (LHZ). They can generally be divided into two groups: direct or semi direct hazard mapping in which the degree of hazard is determined by the mapping expert and indirect hazard mapping in which either statistical or deterministic models are used to predict landslide prone areas based on information obtained from the interrelation between terrain factors and the landslide distribution. With the introduction of GIS, in particular indirect methods gained enormously due to its capacity to handle and analyze data with high spatial variability.

In the context of Sri Lanka, landslide hazard maps are prepared using a model developed under a research project conducted from mid-1989 to mid-1995. This model is based on the analysis of six major terrain factors with sub factors and factor classes collected from more than thousand landslides occurred in Badulla and Nuwaraeliya districts. For the zonation based on this model, field data is collected according to those factors and the corresponding weight maps are prepared manually. GIS is only used finally as an overlaying and reclassifying tool. In this workflow, very laborious effort is needed for the preparation of geology weight map, especially when complex terrain conditions and large amount of data are involved. One of the reasons is that, unlike all other factors where the basic mapping units are areas, the geology map consists of two major parts: lithological units as areas but structural attitudes as linear or point measurements.

In 2009, an approach was discussed how GIS capabilities can be used efficiently to integrate the influence of structural attitudes such as strike or dip directions and dip angles for the preparation of geology weight maps which is an essential part of the LHZ model used in Sri Lanka. Even though the original procedure was based on manual weighting since then, the newly introduced automated procedure has been used by National Building Research Organization to accelerate the mapping procedure.

Under this study, a statistical comparison and an assessment were done between the two procedures and necessary modifications to the latter, that is to the automated procedure is proposed to enhance the accuracy of the method.

Key words: landslide hazard zonation, geology weight, GIS

1. INTRODUCTION

The term landslides comprise almost all varieties of mass movements on slopes including rock falls, topples and debris flows that involve little or no true sliding [Varnes, 1984]. Landslides occur when the critical combinations of many internal and external causative factors are met with a triggering event such as intense rainfall, earthquake shaking, volcanic eruption, rapid snow melt, rapid change of water level, storm waves or rapid erosion that causes a quick increase in shear stress or decrease in shear strength of the slope material.

In many countries, slopes which stood safe for centuries are now frequented by landslides and hence socioeconomic losses due to its impact are growing. This is mainly due to the expansion of human activities into more susceptible hill slopes under the pressure of increasing population and associated demands for housing and infrastructure facilities. Though this has reduced sustainable development efforts today more than ever before especially in developing countries, practice has shown that adequate hazard mitigation is possible.

Landslide hazard zonation involves one of the most complex analysis of interrelated terrain factors such as
lithology and the structural attitude of the rocks, weathering conditions, soil types, properties and their thicknesses, slope gradients and forms, hydrological conditions, land use and management, and integration of expert opinions together in order to evaluate the hazard levels.

The joint analysis of all these terrain variables in relation to the spatial distribution of landslides has gained enormously by the introduction of GIS, the ideal tool for the analysis of parameters with high degree of spatial variability [Van Westen, 2000]. However, in a GIS based analysis, an essential part is to have factor maps as area features (polygons) such as land use or soil type to establish weight values and to determine relationships between these factors.

In the context of Sri Lanka, landslide hazard maps are prepared using a model developed under a research project conducted from mid-1989 to mid-1995 (Table 1). This model is based on the analysis of six major terrain factors with sub factors and factor classes collected from more than thousand landslides occurred in Badulla and Nuwaraeliya districts. For the zonation based on this model, field data is collected according to those factors, sub factors and factor classes, and the corresponding weight maps are prepared manually. GIS is only used finally as an overlaying and reclassifying tool. In this manual workflow, very laborious effort is needed for the preparation of geology weight maps, especially when complex terrain conditions and large amount of data are involved. One of the reasons is that, unlike all other factors where the basic mapping units are areas, the geology map consists of two major parts: lithological units as areas but structural attitudes such as strike or dip directions and dip angles of the rock as linear or point measurements where the weights cannot be directly assigned.

In 2009, a paper titled “Integration of deviation and dip angle concepts using GIS in landslide hazard zonation in Sri Lanka” presented a methodology which can be used to integrate the influence of linear and point measurements of structural attitudes into the analysis using GIS and, automated the manual procedure of the preparation of geology weight maps. Even though the original procedure was based on manual weighting, since then, the newly introduced automated procedure has been used by NBRO to accelerate the mapping procedure.

The present study focuses to compare and assess both the manual and the automated procedures and to propose effective modifications to enhance the accuracy of the latter that is the automated procedure which is very convenient, effective and efficient.

2. LANDSLIDE HAZARD ZONATION IN SRI LANKA

2.1 General background

Sri Lanka is an island located in the Asia–Pacific region between northern latitude of 5° 55’ and 9° 51’
and eastern longitude of 79° 41' and 81° 53' having an area of 65,610 km² with total population close to 20 million (Fig. 1). Geologically, nine-tenths of the country is underlain by highly crystalline metamorphic rocks of Precambrian age.

Among the natural hazards, landslides are attracting increasing attention especially in the central highland (Fig. 1) as a major and a frequent disaster which is directly associated with monsoon rains. The Central Highland solely comprises of high grade metamorphic rocks such as Charnockite, Quartzite, Marble and other Gneissic rocks. Major parts of twelve districts (Fig. 1), namely Badulla, Monaragala, Nuwaraeliya, Matale, Kandy, Kegalle, Kurunegala, Rathnapura, Kalutara, Galle, Mataraka and Hambantota which cover the total area of about 20,000 km² (30%) of the country, are considered to be landslide prone in Sri Lanka.

Presently, for the prediction of occurrence of landslides, a model developed by the Landslide Research and Risk Management Division (LRRMD) of Table 1: Relative weightings for major factors, sub factors and factor classes based on the NBRO model (Landslide studies and services division, National Building Research Organization, 1995)

| Major factors & Max. weighting | Sub factors & Maximum weighting | Sub factor elements (factor classes) | X | Z |
|--------------------------------|--------------------------------|--------------------------------------|---|---|
| Lithology                      | 8                              | Marble                               | very low | 0 |
|                                |                                | Weathered rock                      | low | 1 |
|                                |                                | All others                           | medium | 3 |
|                                |                                | Charnockite, Granulite or bedrock not exposed | high | 5 |
|                                |                                | Quartzite                           | very high | 8 |
|                                |                                | Dip & scarp 71-90                    | very low | 0 |
|                                |                                | Dip & scarp 56-70                    | low | 1 |
|                                |                                | Dip 11-30, scarp 46-55 & all intermediate slopes | medium | 2 |
|                                |                                | Dip 10-15, scarp 31-45               | high | 3 |
|                                |                                | Dip 31-55, scarp 0-30                | very high | 4 |
|                                |                                | Angle 26-120                        | very low | 0 |
|                                |                                | Angle 11-25 or 121-155               | low | 2 |
|                                |                                | Angle 15-180                        | high | 4 |
|                                |                                | Angle 18-20                         | very high | 6 |
|                                | To be decided on ease to ease basis | To be decided on ease to ease basis | very low | 0 |
| Other discontinuities          | 2                              | Bare bedrock                        | very low | 0 |
| Soil cover (m)                 | 10                             | Colluvium <1, Residual <2.5          | low | 2 |
|                                |                                | Colluvium 1-3, Residual 2-8          | medium | 8 |
|                                |                                | Colluvium 3-8, Residual >8           | high | 9 |
|                                |                                | Colluvium >8, Residual >8            | very high | 10 |
| Slope range & category (degrees) | 25                             | Slope category I (0-40)              | very high | 25 |
|                                |                                | Slope category II (1-40)             | high | 16 |
|                                |                                | Slope category III (11-17)           | medium | 13 |
|                                |                                | Slope category IV (11-17)            | low | 7 |
|                                |                                | Slope category V (0-10)              | very low | 5 |
|                                | Hydrological map unit area (sq. km) | Relief >150                         | very low | 5 |
|                                |                                | Relief >150                         | medium | 2 |
|                                |                                | Relief 150-350                      | very high | 7 |
|                                |                                | Area 0-0.07 or > 0.5                 | very low | 1 |
|                                |                                | Area 0.07-0.2                       | medium | 2 |
|                                |                                | Area 0-0.2, 0.2                      | very high | 4 |
|                                | Hydrological map unit area (sq. km) | Hydrological map shape (form factor) | very low | 1 |
|                                |                                | Drainage density (km²/ha)            | very low | 1 |
|                                |                                | To be decided on ease to ease basis | medium | 10 |
|                                | Land use & Management           | Tea (Well manage), Coconut, Dense mixed forest and etc. | very low | 3 |
|                                |                                | Tea (Poorly manage), Rubber, Paddy and etc. | medium | 8 |
|                                |                                | Annual Crops, Palms, Rivers, Lakes and etc. | very high | 15 |
|                                | Landform                        | Flat to undulating, Undulating to rolling, Terraced slope, River beds and etc. | very low | 1 |
|                                |                                | Straight, Complex, Terraced, Dissected and etc. | medium | 3 |
|                                |                                | Straight, Complex, Corrugated and etc. | high | 5 |
|                                |                                | Flat to undulating benches on slopes and etc. | very high | 10 |
the National Building Research Organization (NBRO) in 1995 is used (Table 1). Under this model, the followings are considered as major causative factors:
- Bedrock geology and geological structures
- Former landslides and natural soil type including their thickness
- Morphological slope angle (slope ranges)
- Hydrology and drainage conditions
- Land use and management, and
- Landform

Field data is collected according to the above factors using 1:10,000 scale base maps. Then, areas are demarcated manually into the possible smallest uniform polygons for each factor map. On the basis of sub factors and factor classes, respective weights (scores) are assigned to these uniform areas using Table 1. Finally, all weight (score) maps are overlaid to get total weights (scores) for the zonation of hazard levels.

The total process starting from the demarcation of uniform areas for each factor map to the preparation of the individual weight maps is done manually. Then, the mapping units are digitized as polygon features as GIS is used as a map overlaying and reclassifying tool in the next steps of the workflow.

Here, all the factor maps such as land use, soil type etc., where the basic mapping units are made up of areas can be directly used as uniform polygons in GIS and weights can easily be assigned. This holds only partly for the geology map, where lithology as area features but structural attitudes as linear or point features are involved. In the following sections it is discussed in detail how the geology weight map was prepared manually until 2009 and how GIS has been used since then to automate the process.

### 2.2 Geology weight map

Weight maps of geology constitute a major element of landslide hazard zonation. The most important aspect here is that unlike in other factor maps where basic mapping units are areas (polygons), geology map constitutes non-area features such as structural attitudes which have a major influence in assessing slope stability. Here, both lithology and their structures should be considered for the preparation of geology weight maps. The following sub factors are considered in the process and respective weights (scores) are assigned according to Table 2:

1) Type of lithology
2) Magnitude or amount of deviation angle
3) Magnitude or amount of the dip of the bedrock foliation and type of slope
4) Presence of discontinuities, lineaments, faults and master joints

Sub factors (2) and (3) are based on the concept of deviation angle which is defined as the horizontal angle between the azimuth of the slope direction, and the azimuth of the dip direction [Landslide studies and services division, National Building Research Organization, 1995]. The resulting deviation angle will vary in magnitude between zero and 180 degrees.

#### 2.2.1 Work flow of the manual procedure of preparing geology weight map

The base map for starting the work is a hard copy of the geology map with structural attitude values (e.g. strike or dip direction and dip angle of rock foliation) located onto a contour map of the terrain (Fig. 2). The steps performed manually are as follows:

- Divide the topography of the terrain manually into nearly uniform, smallest polygons with respect to slope angle and slope direction

| Geology sub factor | Very low | Low | Medium | High | Very high |
|--------------------|----------|-----|--------|------|----------|
| 1. Lithology Weight | 8        | 11  | 15     | 18   | 25       |
| 2. Deviation angle | 6        | 10  | 15     | 20   | 30       |
| 3. Amount of dip & type of slope | 4 | 6 | 9 | 12 | 15 |

Table 2 Scoring for the sub factors of the geology weight map based on Table 1

Note: NBE = “No Bed Rock Exposures”

Dip, scarp, intermediate slopes are defined by deviation angle

\[
\text{Dip} = \text{Deviation angle} = 0^\circ-45^\circ, \text{Intermediate} = 45^\circ-90^\circ, \text{Scarp} = 90^\circ-180^\circ
\]
considering the contour line spacing and directions (Fig. 2).

- Assign weight values (scores) to these uniform polygons according to the type of lithology (Table 2, first row). E.g., if the lithology is Charnockite, five (5) scores are assigned.

- Determine the deviation angle for each uniform polygon and assign particular weight values (scores). This is done by finding the dip direction of the bed rock foliation and measuring the angle it includes with the slope direction (Fig. 2 and Table 2, second row). The slope direction of each uniform polygon is drawn perpendicular to the contour lines and the deviation angle is measured using the closest measurement of the dip direction. E.g., when the dip direction is 262° and the slope direction is 285°, the deviation angle is 23° and hence two scores are (2) assigned.

- The scores for the amount of dip and type of slope are determined next (Fig. 2 and Table 2, third row). Here it is assumed that the influence of the angle of dip on slope stability depends on the type of slope, whether or not the area is a dip slope (deviation angle 0-60), intermediate slope (dev. angle 60-120) or scarp slope (dev. angle 120-180). E.g., considering the example slope from above with a deviation angle of 23°, and assuming a dip angle of 34°, the area is of type dip slope in the category of dip angle range (31-55) where four (4) scores are assigned.

- Consider major discontinuities such as topographic lineaments, faults and master joints and all slopes that are having close proximity to such features are assigned additional scores (Table 2, fourth row). E.g., in the discussed example there are no major discontinuities close to the area. Thus zero scores are assigned and therefore the total score for the considered polygon is 5+2+4+0=11.

The above process, starting from demarcating uniform polygons to assigning scores manually is subjective and a very laborious work especially when morphologically complex terrains are considered and large amount of data are involved. Therefore, the use of GIS for the process will immensely help to improve the quality and accelerate the total LHZ project. In the following section it is discussed how GIS capabilities can be used effectively to facilitate this work.

### 2.2.2 Work flow of the automated procedure of preparing geology weight maps using GIS

Unlike in the manual procedure, where uniform polygons are demarcated and scores are assigned on paper maps, to automate the process digital data is needed. As input data, a polygon feature class of geology with attributes of lithological units and a point feature class of locations of dip direction and dip angle measurements is used. The analysis can easily be built on raster data structures, here only the process for raster structure is discussed. For the geoprocessing in this project ESRI ArcGIS 9.2 is used, but in principle any system with capabilities for raster processing, in particular a raster algebra calculator, is suited. The steps are as follows:

- Rasterizing the geology map using a suitable grid size (as a rule of thumb, the cell size should be less than 50% of the smallest polygon object to be recognized, here 10 m grid size is used) and reclassify it according to the lithology weights (Fig. 3 a, b, c and Table 2, first row).

- Prepare an aspect layer and an interpolated surface of dip direction layer (Fig. 3 d and e). Here, the method of Inverse Distance Weighting (IDW) is preferred over other interpolating methods. Then, calculate the deviation angle layer using the following logical expression in the raster calculator (Fig. 3 f).

```
con(Abs([Aspect] - [DipDirIDW]) < 180, Abs([Aspect] - [DipDirIDW]), 360 - Abs([Aspect] - [DipDirIDW]))
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Reclassify the output layer of deviation angle according to the given weights (Fig. 3 g and Table 2, second row).

- Prepare an interpolated surface of dip angle layer using IDW method (Fig. 3 h).

- Use this layer together with the original deviation angle layer (Fig. 3 f) prepared in the previous step. Here, the amount of dip angle and the type of slope such as dip slope where deviation angle ranges from 0 to 60°, intermediate slopes where deviation angle ranges from 60 to 120°, and scarp..
slopes where deviation angle ranges from 120 to 180° are considered (Table 2, third row).

- Apply the logical expression below in the raster calculator to assign the given weight values to the pixels which satisfy the following conditions (Fig. 3 and Table 2, third row):
  - Deviation angle range of 0-60 (dip slope) and dip angle ranges of 0-10, 10-30, 30-55, 55-70, 70-90.
  - Deviation angle range of 60-120 (intermediate slope) and dip angle range of 0-90. Here, all intermediate slopes receive two scores regardless of their amount of dip angle.
  - Deviation angle range of 120-180 (scarp slope) and dip angle ranges of 0-30, 30-45, 45-55, 55-70, 70-90.
- Use the linear feature class of discontinuities layer, calculate the Euclidean distance and

\[
\begin{align*}
\text{con}([\text{DevAngle}] & > 0 & \land [\text{DevAngle}] & < 60 & \land [\text{dipAngleIDW}] & > 0 & \land [\text{dipAngleIDW}] & < 10, 3, \\
\text{con}([\text{DevAngle}] & > 0 & \land [\text{DevAngle}] & < 60 & \land [\text{dipAngleIDW}] & > 10 & \land [\text{dipAngleIDW}] & < 30, 2, \\
\text{con}([\text{DevAngle}] & > 0 & \land [\text{DevAngle}] & < 60 & \land [\text{dipAngleIDW}] & > 30 & \land [\text{dipAngleIDW}] & < 55, 4, \\
\text{con}([\text{DevAngle}] & > 0 & \land [\text{DevAngle}] & < 60 & \land [\text{dipAngleIDW}] & > 55 & \land [\text{dipAngleIDW}] & < 70, 1, \\
\text{con}([\text{DevAngle}] & > 0 & \land [\text{DevAngle}] & < 60 & \land [\text{dipAngleIDW}] & > 70 & \land [\text{dipAngleIDW}] & < 90, 0, \\
\text{con}([\text{DevAngle}] & > 60 & \land [\text{DevAngle}] & < 120 & \land [\text{dipAngleIDW}] & > 0 & \land [\text{dipAngleIDW}] & < 90, 2, \\
\text{con}([\text{DevAngle}] & > 120 & \land [\text{DevAngle}] & < 180 & \land [\text{dipAngleIDW}] & >= 0 & \land [\text{dipAngleIDW}] & <= 30, 4, \\
\text{con}([\text{DevAngle}] & > 120 & \land [\text{DevAngle}] & < 180 & \land [\text{dipAngleIDW}] & > 30 & \land [\text{dipAngleIDW}] & <= 45, 3, \\
\text{con}([\text{DevAngle}] & > 120 & \land [\text{DevAngle}] & < 180 & \land [\text{dipAngleIDW}] & > 45 & \land [\text{dipAngleIDW}] & <= 55, 2, \\
\text{con}([\text{DevAngle}] & > 120 & \land [\text{DevAngle}] & < 180 & \land [\text{dipAngleIDW}] & > 55 & \land [\text{dipAngleIDW}] & <= 70, 1, \\
\text{con}([\text{DevAngle}] & > 120 & \land [\text{DevAngle}] & < 180 & \land [\text{dipAngleIDW}] & > 70 & \land [\text{dipAngleIDW}] & <= 90, 0)\end{align*}
\]

Fig. 3 Steps of the preparation of the geology weight (derived) map using GIS
reclassify it according to the given weights (Fig. 3j, k and Table 2, fourth row).

- Finally, sum all the four weight layers (Fig. 3c, g, i and k) together to calculate the total weights for the geology weight map (Fig. 3l).

3. GENERAL CHARACTERISTICS OF TWO METHODS

Some of the typical characteristics of the manual as well as the GIS based automated procedures are listed in the above comparison (Table 3). They can be used for a better understanding of the advantages and disadvantages of the procedures and how and why such differences exist.

4. ASSESSMENT AND COMPARISON OF TWO METHODS

For the assessment and comparison, 1:10,000 scale geology and contour map of 87/03 with 40 km² was used and the weight map of geology was prepared using the original methodology of manual procedure and the later developed automated procedure. The manually weighted polygon map was digitized by the GIS laboratory in NBRO. The polygons were then converted into 3m x 3m pixels (same size as in the automated procedure). There were total of 4,445,781 pixels in the analysis. The weight values of the corresponding pixels in the map prepared by the automated procedure were compared against the map prepared using manual procedure within the GIS environment, and the following results were obtained (Tables 4, 5 & 6).

Statistical comparison

F-test was used to compare the values derived from two methods using MINITAB 16.

\[ H_0 : \text{Variance of Test Method 1} = \text{Variance of Test Method 2} \]

\[ H_1 : \text{Variance of Test Method 1} \neq \text{Variance of Test Method 2} \]

According to the results, p-value (0.000) is less than 0.05, therefore \( H_0 \) is rejected at 5% significance level. Hence, the results obtained from the automated procedure have significantly vary from the results obtained from the manual procedure.

5. DISCUSSION AND CONCLUSION

GIS has proved here as an ideal tool which can be used to integrate linear or point measurements in direct or indirect landslide hazard zonation. The method is extremely efficient and effective compared to the manual procedure and this has significantly improved the quality and accelerated the whole landslide hazard zonation process in Sri Lanka where large amount of field data was available, but final hazard maps had not been prepared before 2009.

Even though, there is no guarantee that the manual procedure delivers precise results, the manual procedure is considered as the standard procedure in the work flow and hence the weight values obtained from the automated procedure is compared against the manual procedure. According to the F-test, it is proved that the results obtained from the automated procedure
have significantly vary from the results obtained from the manual procedure. Therefore, it can be concluded that the weight values obtained from the automated procedure deviate significantly from the corresponding weight values obtained from the manual procedure. Thus, it is advisable to make necessary changes to the automated procedure to obtain weight values more closely comparable to the weight values obtained from the manual procedure.

### 6. RECOMMENDATIONS

To minimize most of the deviations and dissimilarities of weight values in the map prepared by the automated procedure, following practices can be recommended.

**Practice-01:**

Use of barrier polylines appropriately is an essential step. While following the same steps explained in the automated procedure, more thorough attention, emphasis and expert opinion has to be included for using barrier polylines appropriately for the preparation of interpolated surfaces of dip direction and dip angle layers. Here, it must be considered to include barrier polylines along, 1) fold axis, 2) fault axis, 3) any major lineaments or discontinuities, and major rivers or ridges and 4) lithological boundaries.

**Practice-02:**

Instead of using interpolated surfaces of dip angle and dip direction layers, as in the manual procedure, subjective decisions can be taken by the expert to demarcate the effective zone of each measurement of structural attitude by defining barrier polylines around the area, and assign the same value to all the pixels within the defined area while keeping the remaining work flow of the automated procedure unchanged.

In both the practices, it is strongly advice to take the decision of appropriate barrier polylines by the field geologist considering the field situations and regional geological structures to come out with worthy results.

Recent application proved to be very significantly improved the quality of the Geology weight map prepared by automated procedure achieving the expected accuracy while accelerating the process.

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**Table 4** Deviation of the weight value of automated procedure against the manually assigned weight, and its count

| Deviation | Count | Deviation | Count |
|-----------|-------|-----------|-------|
| -10       | 488   | 0         | 1288410 |
| -9        | 1850  | 1         | 237393  |
| -8        | 27159 | 2         | 608887  |
| -7        | 4569  | 3         | 227029  |
| -6        | 107312| 4         | 400475  |
| -5        | 56194 | 5         | 106735  |
| -4        | 212440| 6         | 242957  |
| -3        | 156126| 7         | 17145   |
| -2        | 431534| 8         | 55455   |
| -1        | 161821| 9         | 1909    |
|           |       |           | 10      |

**Table 5** Summary Statistics derived from F-test

| Procedure of weighing | N   | Mean | St. Dev | SE Mean |
|-----------------------|-----|------|---------|---------|
| Weight value of manual procedure | 4445781 | 10.37 | 2.62 | 0.0012 |
| Weight value of automated procedure | 4445781 | 9.82 | 2.5 | 0.0012 |

**Table 6** F-test output

| Test | Method | DF1 | DF2 | Statistic | P-Value |
|------|--------|-----|-----|-----------|---------|
| F-test (normal) | 4445780 | 4445780 | 1.1 | 0.000 |