Integration of Deviation and Dip Angle Concepts Using GIS in Landslide Hazard Zonation in Sri Lanka

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Abstract

Many techniques have been proposed for landslide hazard zonation (LHZ). They can be generally 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 landscape 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, LHZ maps are prepared using a model developed based on the analysis of more than thousand major landslides during a five year period from mid 1989 to mid 1995. For the zonation based on this model, field data are collected according to six major 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 maps, especially when complex terrain conditions and large amount of data are involved. One of the reasons is that, unlike all other factors where 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 this paper, an approach is 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.

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 vulnerable slopes under the pressure of increasing population and associated demands for infrastructure facilities. Though this has reduced a sustainable development today more than ever before especially in developing countries, practice has shown that adequate hazard mitigation is possible.

LHZ involves one of the most complex analysis of interrelated terrain factors such as lithology and the structural attitude of the rocks, weathering conditions, soil 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 (e.g. VAN WESTEN, 2000).

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. However, this paper presents a methodology which can be used to integrate the influence of linear and point measurements of structural attitudes such as strike or dip directions and dip angles and, automate the manual procedure using GIS for the preparation of geology weight maps in the process of LHZ mapping in Sri Lanka.

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 km^2 with total population close to 20 million (see Fig. 1). Geologically, nine-tenths of the country is underlain by highly crystalline metamorphic rocks of Precambrian age.

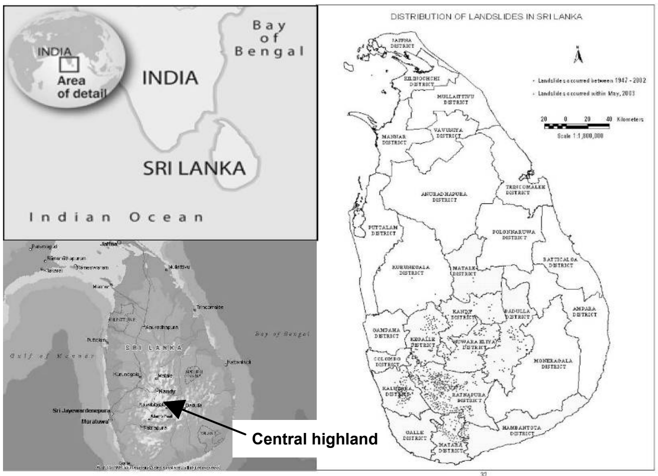

Fig. 1: Maps of Sri Lanka showing the central highland and landslide prone districts

Among the natural hazards, landslides are attracting increasing attention especially in the central highland (see Fig. 1) as a major and frequent disaster which is directly associated with monsoon[1] rains. The central highland solely comprises of high grade metamorphic rocks such as Charnockite, Quartzite, Marble and other Gneissic rocks. Major parts of ten districts (see Fig. 1), namely *Badulla, Nuwaraeliya, Rathnapura, Kegalle, Kandy, Matale, Kalutara, Galle, Matara* and *Hambantota* which cover the total of about 20.000 km^2 (30.7 %) of the land area, are considered to be landslide prone in Sri Lanka.

Presently, for the prediction of occurrence of landslides, a model developed by the Landslide Studies and Services Division (LSSD) of the National Building Research Organization (NBRO) in 1995 is used (see Tab. 1). Under this model, the following items 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 base maps. Then, areas are demarcated manually into uniform polygons for each factor map. On the basis of sub factors and factor classes, scores are assigned to these uniform areas using Table 1. Finally, all weight maps are overlaid to get total 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, slope category etc., where the basic mapping units are made up of areas can be directly used as uniform polygons in GIS and weights can be easily 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 is prepared manually until now and how GIS can be used to automate this process.

[1] The seasons are distinguished only by means of the timing of the two monsoons and the transitional periods separating them, called inter-monsoon seasons. The Southwest monsoon is from May to September and the Northeast monsoon from December to February. The inter-monsoon periods are from March to April and from October to November.

Table 1: Relative weightings for major factors, sub factors and factor classes based on the NBRO model (NBRO user manual, 1995)

Major factors & Max. weighting	**Sub factors & Max. weighting**	**Sub factor elements (factor classes) Linguistic rating(x) & Scores(z)**	**x**	**z**
Bedrock Geology & Geological structures 20	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
	Amount of dip & type of slope 4	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 0-10, scarp 31-45	high	3
		Dip 31-55, scarp 0-30	very high	4
	Deviation angle (degrees) 6	Angle 26-120	very low	0
		Angle 11-25 or 121-155	low	2
		Angle 156-180	high	4
		Angle 0-10	very high	6
	Other Discontinuities 2	To be decided on case to case basis	very low	0
			very high	2
Type of natural soil cover & thickness 10	Soil cover (m) 10	Bare bedrock	very low	0
		Colluvium <1, Residual <2	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 25	Slope range & category (degrees) 25	Slope category I (>40)	very high	25
		Slope category II (31-40)	high	16
		Slope category III (17-31)	medium	13
		Slope category IV (11-17)	low	7
		Slope category V (0-10)	very low	5
Hydrology & Drainage 20	Relief amplitude(m) 5	Relief >350	Very low	1
		Relief 0-170	medium	2
		Relief 170-350	very high	5
	Hydrological map unit area (sq. km) 4	Area 0-0.07 or > 0.5	very low	1
		Area 0.07-0.2	medium	2
		Area 0.2-0.5	very high	4
	Hydrological map unit shape (form factor 4	0.6-1.0	very low	1
		0.3-0.6	medium	2
		< 0.3	very high	4
	Drainage density (km/sq. km) with or without soil cover 5	With >5 or without >10	very low	1
		With 3-5 or without 6-10	medium	2
		With 0-3 or without <6	very high	5
	Proximity to water bodies 2	To be decided on case to case basis	very low	0
			medium	1
			very high	2
Land use & Management 15	Land use & Management 15	JT1, JC, JQ, JWb, W1, S1	very low	3
		JT2,JR,JWp,HP,HK,HM,HW,W2,W3,W4, S2,S4	medium	8
		HA, G1, G2, S3, N1, N2, N3, N4	very high	15
Landform 10	Landform 10	F11,F12,F31-35,F43,F91-92, F94,A10-13, X1,X2	very low	1
		F41,F42,F44-48,F53	medium	3
		F51,F52,F54-58,X13,X14	high	5
		F61,F62,F71-74,F81-83, F92,X11,X15	very high	10

2.2 Geology Weight Map

Weight maps of geology constitute a major element of LHZ mapping. 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. Therefore, 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 scores are assigned according to Table 2:

(1) Type of lithology.
(2) Magnitude of deviation angle
(3) Steepness 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[2], and the azimuth of the dip direction[3] (NBRO user manual, 1995). The resulting deviation angle will vary in magnitude between zero and 180 degrees.

2.2.1 Manual Steps for Preparing Geology Weight Maps

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 (see Fig. 2). The steps performed manually are as follows:

- Divide the topography of the terrain manually into nearly uniform polygons with respect to slope angle and slope direction considering contour line spacing and directions (see Fig. 2).
- Assign weight values (scores) to these uniform polygons according to the type of lithology (Tab. 2, first row). E.g., if the lithology is Charnockite, five (5) scores are assigned.
- Determine the deviation angle for each 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 (see Fig. 2 and Tab. 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 (see Fig. 2 and Tab. 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 range (31-55) where four (4) scores are assigned.

[2] The slope direction is the compass bearing in the downhill direction of the steepest slope.
[3] The dip direction is the horizontal line orthogonal to the foliation strike, in the down dip direction.

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

	Geology sub factor	Very low	Low	Medium	High	Very high
1	Lithology Weight = 8	Marble 0	Weathered rock 1	All others 3	Charnockite Granulite & NBE 5	Quartzite 8
2	Deviation angle Weight = 6	--	All NBE & 26 – 120 0	11 – 25 121 – 155 2	156 – 180 4	0 –10 6
3	Amount of dip & type of slope Weight = 4	All NBE, dip & scarp 71 – 90 0	Dip & scarp 56 – 70 1	Dip 11 -30 Scarp 46 – 55 All intermediate 2	Dip 0 – 10 Scarp 31 – 45 3	Dip 31 – 55 Scarp 0 – 30 4
	Note	Dip, scarp, intermediate slopes are defined by deviation angle Dip=Dev. angle 0^0– 60^0 , Intermediate 60^0– 120^0, Scarp 120^0 – 180^0				
4	Discontinui-ties, faults, lineaments Weight = 2	If absent 0	--	--	--	If present 2
	Note	NBE = "No Bed Rock Exposures"				

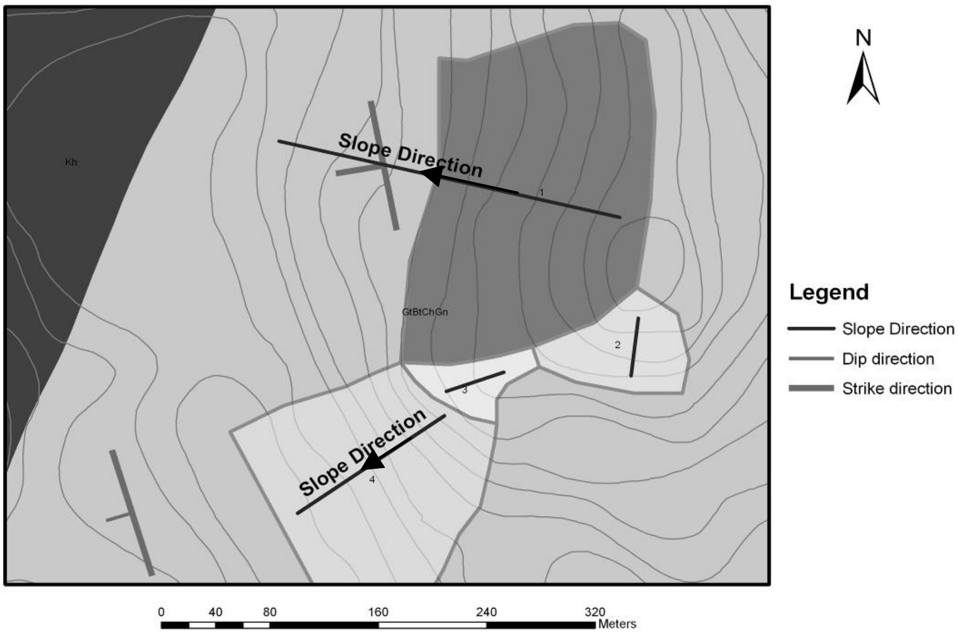

Fig. 2: Steps in the manual preparation of geology weight map (derived map)

- Consider major discontinuities such as topographic lineaments, faults and master joints and all slopes that are having close proximity to such features and assign additional scores (Tab. 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 How to Automate the Process Using GIS

Unlike in 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 be built on vector or 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;

- Rasterize 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 (see Fig. 3a, b, c and Tab. 2, first row).
- Prepare an *aspect* layer and an interpolated surface of *dip direction* layer (Fig. 3d and e). Here, the method of Inverse Distance Weighting (IDW)[4] is preferred over other interpolating methods. Then, calculate the *deviation angle* layer using the following logical expression in the raster calculator (see Fig. 3f).

  con(Abs([Aspect] - [DipDirIDW]) < 180, Abs([Aspect] - [DipDirIDW]),
  360 - Abs([Aspect] - [DipDirIDW]))

  Reclassify the output layer of deviation angle according to the given weights (see Fig. 3g and Tab. 2, second row).
- Prepare an interpolated surface of *dip angle* layer using IDW method (see Fig. 3h). Use this layer together with the original *deviation angle* layer (see Fig. 3f) 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 (Tab. 2, third row).

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4 IDW is an exact deterministic interpolator. Therefore, pixel values in the interpolated surface do not go beyond the limits of input data, which is needed for dip directions (0°– 360°) and dip angle (0°– 90°) are concerned. The ability to control the power, number of points and barrier polylines are other important characteristics to get a representative prediction surface for data like angles and directions.

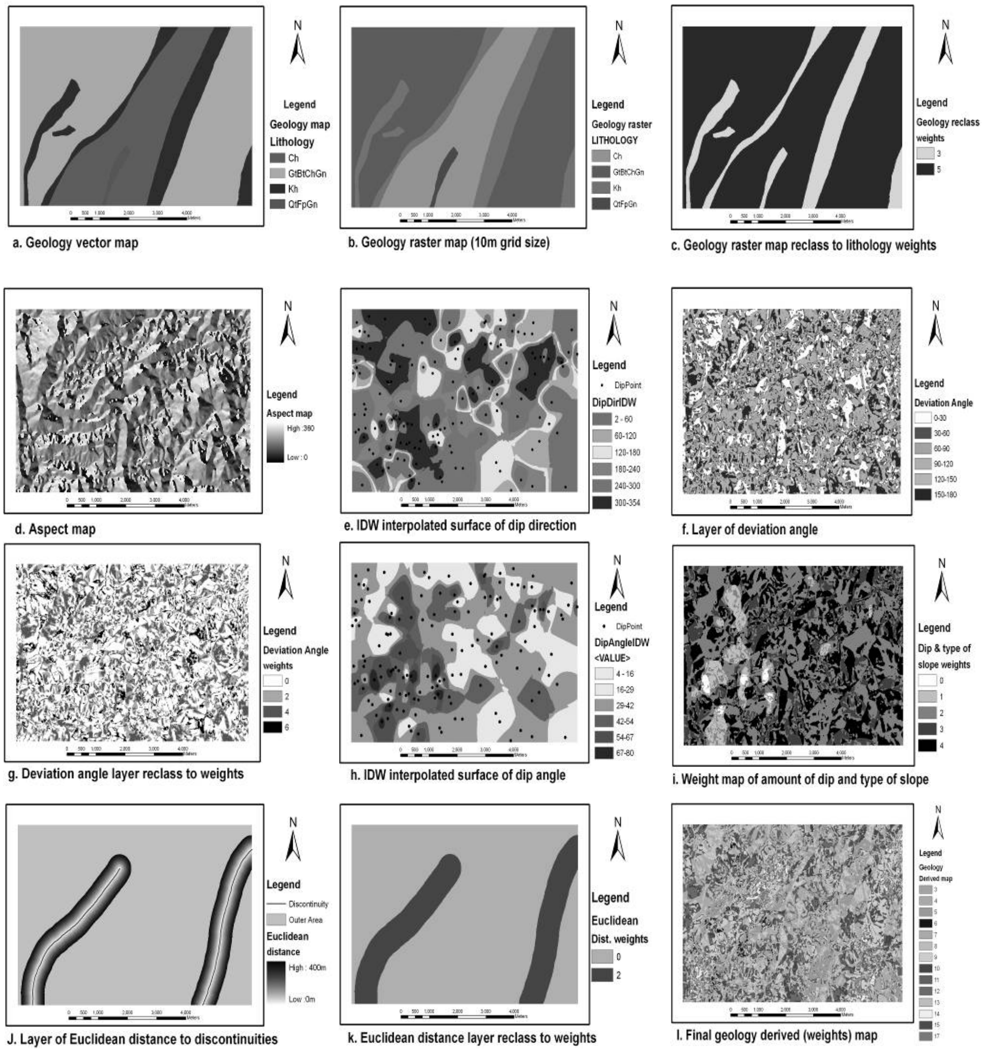

Fig 3: Steps of the preparation of the geology derived map (weight map) using GIS

Apply the logical expression below in the raster calculator to assign the given weight values to the pixels which satisfy the following conditions (see Fig. 3i and Tab. 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 will 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.

```
con([DevAngle] >= 0 & [DevAngle] <= 60 & [dipAngleIDW] >= 0 & [dipAngleIDW] <= 10, 3,
con([DevAngle] >= 0 & [DevAngle] <= 60 & [dipAngleIDW] > 10 & [dipAngleIDW] <= 30, 2,
con([DevAngle] >= 0 & [DevAngle] <= 60 & [dipAngleIDW] > 30 & [dipAngleIDW] <= 55, 4,
con([DevAngle] >= 0 & [DevAngle] <= 60 & [dipAngleIDW] > 55 & [dipAngleIDW] <= 70, 1,
con([DevAngle] >= 0 & [DevAngle] <= 60 & [dipAngleIDW] > 70 & [dipAngleIDW] <= 90, 0,
con([DevAngle] > 60 & [DevAngle] <= 120 & [dipAngleIDW] >= 0 & [dipAngleIDW] <= 90, 2,
con([DevAngle] > 120 & [DevAngle] <= 180 & [dipAngleIDW] >= 0 & [dipAngleIDW] <= 30, 4,
con([DevAngle] > 120 & [DevAngle] <= 180 & [dipAngleIDW] > 30 & [dipAngleIDW] <= 45, 3,
con([DevAngle] > 120 & [DevAngle] <= 180 & [dipAngleIDW] > 45 & [dipAngleIDW] <= 55, 2,
con([DevAngle] > 120 & [DevAngle] <= 180 & [dipAngleIDW] > 55 & [dipAngleIDW] <= 70, 1,
con([DevAngle] > 120 & [DevAngle] <= 180 & [dipAngleIDW] > 70 & [dipAngleIDW] <= 90,
0)))))))))))
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- Use the linear feature class of discontinuities layer, calculate the Euclidean distance and reclassify it according to the given weights (see Fig. 3j, k and Tab. 2, fourth row)

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

	Manual Procedure	**GIS Procedure**
1	Very laborious – depend on person's efficiency.	Very fast comparing to manual procedure – depend on the capacity of computer.
2	Subjective results depending on the person's experience and correctness of demarcating uniform polygons.	Objective results depending on grid resolution (pixel size).
3	Sizes of uniform polygons vary according to contour style (terrain morphology).	Equal and uniform grid size is considered over the whole terrain.
4	Uniformity within the polygon depends on person's visual inspection and accuracy of contour data.	Uniformity within the polygon depends on contour accuracy and grid resolution.
5	The boundaries between polygons follow topographic changes such as ridges and valleys as well as margins where slope direction and slope gradient changes.	Boundaries detected from the grid need not to follow such topographic boundaries unless detailed breaklines are used. Therefore, selection of appropriate grid size is very important. Smaller grid sizes are preferred.
6	When assigning scores for 2nd and 3rd steps in Table 2, exact value of the dip direction and dip angle of the closest reading is considered. Therefore, the weights are more subjective.	The interpolated value of the dip direction and dip angle values of the exact pixel is used. Therefore, weights are more objective and depend on the quality and distribution of input data and interpolation method.
7	There is a chance to select a suitable reading appropriately when polygons close to the axis of synform, antiform, faults are considered.	If barrier lines are not used in the interpolation where synform, antiform, faults are present, interpolated values of the pixels close to the axis will have erroneous results.
8	Output can be used as factors for any models such as heuristic or statistical.	Output can be used as factors for any models such as heuristic or statistical.
9	Process become more time consuming and complicated with the introduction of more factor classes and more sub factors such as apparent dip, over dip- under dip concepts.	Process is the same with the introduction of more factor classes and more sub factors such as apparent dip, over dip- under dip concepts.

3 Discussion and Conclusion

Some of the typical characteristics of the manual as well as the GIS based methods are listed in the following comparison. They can be used for a better understanding of the advantages and disadvantages of the procedures.

As conclusions, GIS has proved here as an ideal tool which can be used to integrate linear or point measurements in direct or indirect LHZ mapping. The method is extremely efficient and effective compared to the manual procedure and this will definitely improve the quality and accelerate the whole LHZ mapping project in Sri Lanka where large amount of field data are already available, but final hazard maps have not been yet produced.

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