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Hazard Assessment of Debris Flows by Statistical Analysis and GIS in Central Taiwan

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Abstract: This paper aims to build an analytical process of assessing debris-flow hazards using multivariate analysis and geographic information system (GIS) techniques. The watershed of the Chen-Yu-Lan River is investigated in this study. Factors that are believed to be critical in the occurrence of debris flow are identified and considered in the assessment of debris-flow hazards. These factors used for assessing the debris-flow hazard are: (1) rock formation, (2) fault length, (3) naked-land area, (4) slope angle, (5) slope aspect, (6) stream slope, (7) watershed area, (8) form factor, and (9) cover and management factor. Using the spatial analysis feature of GIS, the indexes of these factors are calculated. By using principal component analysis (PCA) and discriminant analysis (DA) of all indexes according to each factor, the discriminant function of overall debris-flow hazard at any particular creek in the Chen-Yu-Lan River may be assessed. The applicability of the proposed approach for hazard assessment of debris-flow in the watershed of the Chen-Yu-Lan River has been confirmed with other researches and field observations in recent debris-flow events.

Keywords: debris-flow, hazard assessment, geographic information system, multivariate analysis

1. Introduction

Taiwan is an island with one third of its area located in mountainous zones. Due to the scarcity of usable land, many housing units and farmhouses have been built at the hillsides and on the hills. Besides, earthquakes and typhoons occur frequently because Taiwan is on the Circum-Pacific Earthquakes Belt and Western-Pacific Typhoon Path. Moreover, landslides and severe erosion over the years on steep hills that consists of relatively erosive geological materials have resulted in abundant colluvial accumulation especially after the 921 Chi-Chi Earthquake. The average annual rainfall is more than 2500 mm and usually contributed by severe rainstorms caused by typhoons. During heavy rainfalls, the geological materials and colluvium are easily weakened, which often lead to a debris flow. As a result, the casualties, property loss, and structure damage caused by debris flows have increased dramatically in recent years.

There have been many cases of debris-flow damages in Taiwan, such as Ton-Men Valley

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in Hualien County in 1990 and the watershed of Chen-Yu-Lan River (Figure 1). in Nanto County in 1996 and 2001. Four hundred and eighty five (485) creeks in Taiwan are classified as hazardous debris-flow creeks according to the maps published by the Council of Agriculture [1]. These hazardous debris-flow creeks are judged to have debris-flow hazards based on evaluation of the average stream slope, watershed area, and the potential for damages to the downstream village. The procedure for identifying hazardous debris-flow creeks is shown in Figure 2. [2] Therefore, the relative potential of these creeks for debris flows becomes of great importance in land resources investigation and sloping land development.

A geographic information system (GIS) is a suitable means to process spatial data and to display results. Basically, GIS is a convenient tool to handle a variety of data sets, to provide an effective assessment of environmental controls, and to conduct a decision-making analysis. Application of GIS can provide the spatial display that is better than using traditional methods without display. Gupta and Joshi [3] used GIS in assessing landslides hazard zones. The GIS-based approaches in assessing debris-flow hazards were reported in recent years [4-7]. In this research, GIS is applied to process various data and display hazard assessment results of potential debris flows.

Arc/Info (version 3.4.2) and ArcView (version 3.2) programs for personal computer developed by ESRI Co. Ltd. and a GIS software WinGrid, developed by Professor Chao-Yuan Lin in the Department of Water and Soil Conservation in National Chung-Hsing University in Taiwan, are used for this research.

2. The scope of investigation

The watershed of Chen-Yu-Lan River, located in the central part of Taiwan, was selected to be the study site as shown previously in Figure 1. Chen-Yu-Lan River originates from the north peak of Yu Mountain with an elevation of 3910 m. Chen-Yu-Lan River is one of the upper rivers of Zhuoshui River system, which is the largest river system in Taiwan. Chen-Yu-Lan River has a length of 42.4 km with an average declination slope of 5%, and its watershed area is about 45,000 hectares. From July 31st through August 1st in 1996, the heavy rainfall brought by Typhoon Herb triggered 12 debris flows in the watershed of the Chen-Yu-Lan River (see Figure 3). These 12 creeks, given ID from h1 to h12, were selected and categorized as the group of higher susceptibility to debris-flow initiations in this research. The other nine creeks (given ID from n1 to n9 in Figure 4), which has never had occurred debris flows in recent 20 years and were determined not to have potential debris-flow hazard by the Council of Agriculture, were selected and categorized as the group of lower susceptibility to debris-flow initiations. These 21 creeks were selected for establishing the database of debris flow in this research.

3. Methodology

3.1 Assessment processes

The traditional beginning task for hazard assessment of potential debris flows is field investigation [8-11]. However, such investigation is costly in time and money. In our study, the watershed databases of topography, geology, and hydrology can be evaluated as the contributing factors of debris-flow initiation by utilizing the capability of spatial analysis of GIS. The first task is to choose the data sets contributing debris-flow occurrence. The second task is to obtain a variety of the contributing factors by processing the digital data in GIS software. The third task is to analyze each contributing factor by multivariate analysis on the data. Through this statistical operation, the matrix of eigen vectors for the first to fifth principal components can be calculated by SPSS software. The number of significant principal components is determined using Kaiser's rule. The fourth task is using Fisher's linear discriminant analysis to establish discriminant function for these five principal components. Then any creek in the watershed of Chen-Yu-Lan River can be grouped into two categories. One is the group of higher susceptibility to debris-flow initiations when the discriminant scores (DA scores) are lower than 0.33 in these creeks. The other is the group of lower susceptibility to debris-flow initiations when the discriminant scores are higher than 0.33 in these creeks. Finally, hazard of higher susceptibility to debris-flow initiations can be assessed by classifying discriminant scores into 3 categories. The analytical results are compared with the 16 creeks of Chen-Yu-Lan River determined to have potential debris-flow hazards by the Council of Agriculture to test the applicability of this hazard assessment approach.

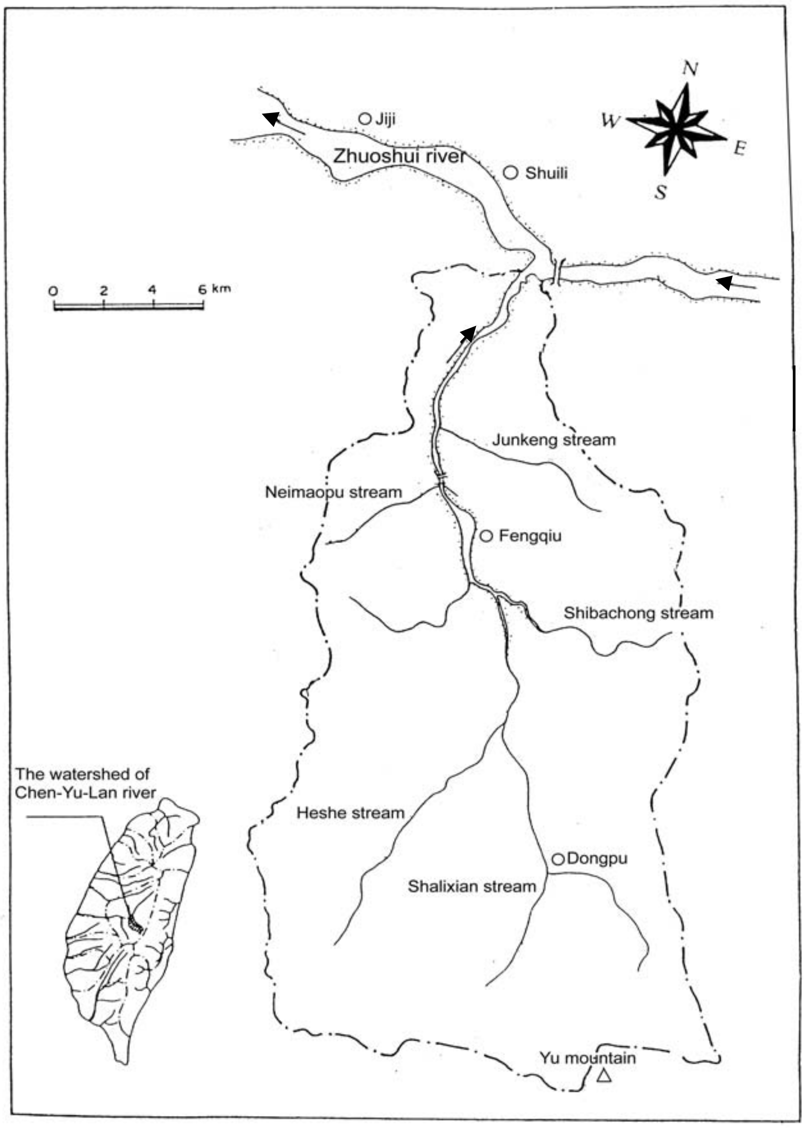


Figure 1. The watershed of the Chen-Yu-Lan River in Taiwan

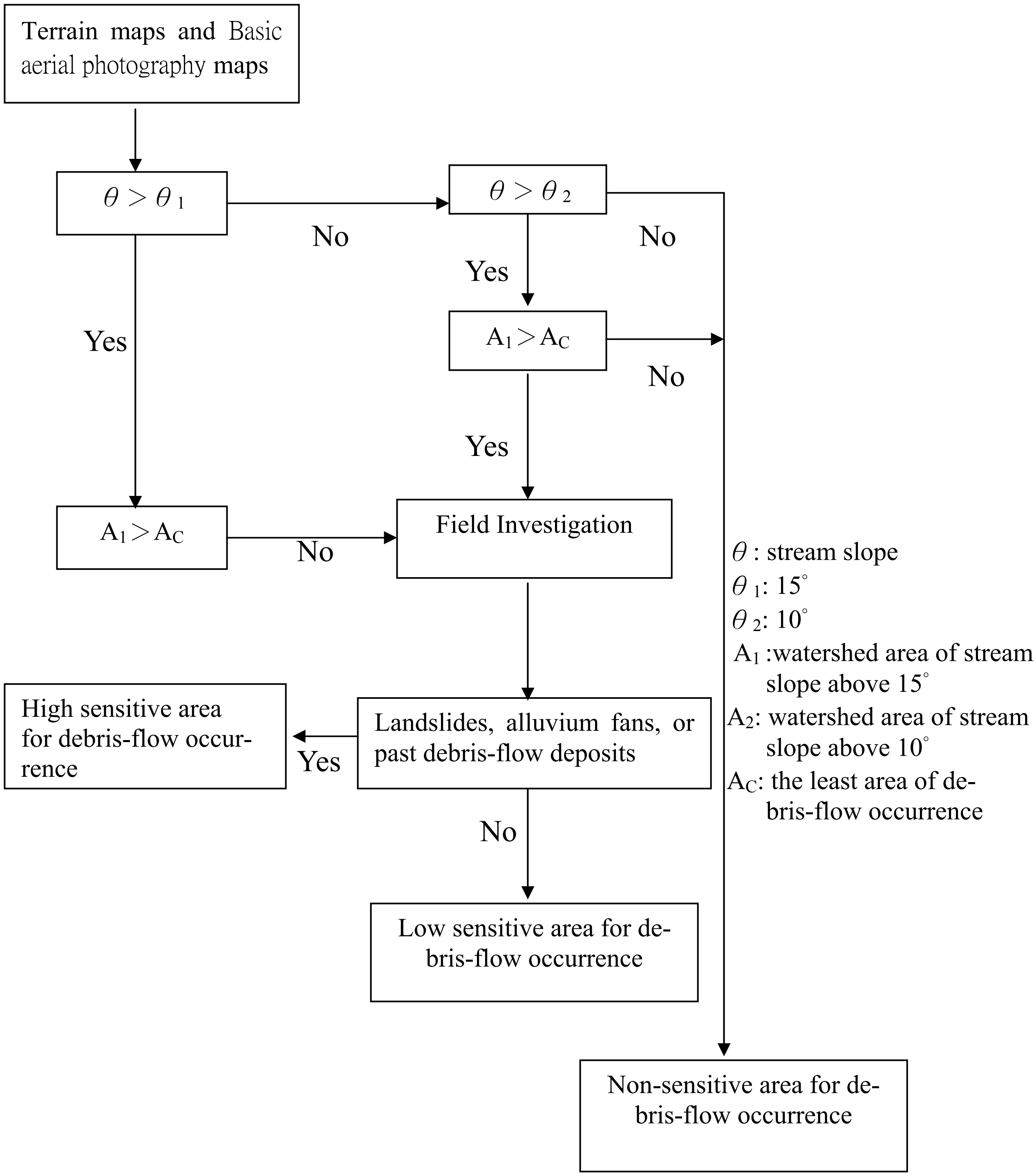


Figure 2. Processes for identifying hazardous debris-flow creeks in Taiwan [2]

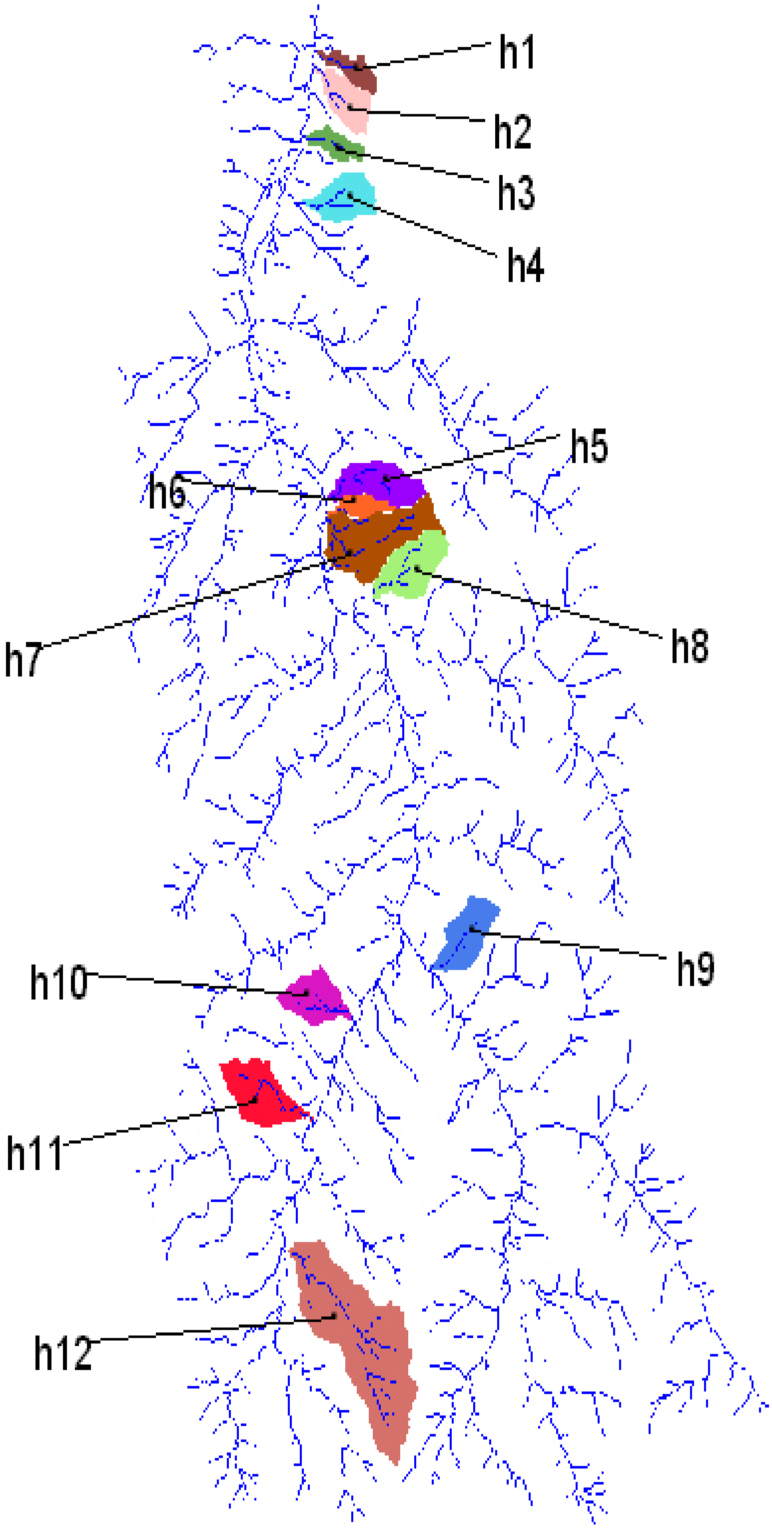


Figure 3. The 12 creeks classified in the group of higher susceptible for debris-flow initiation (potential debris flow)

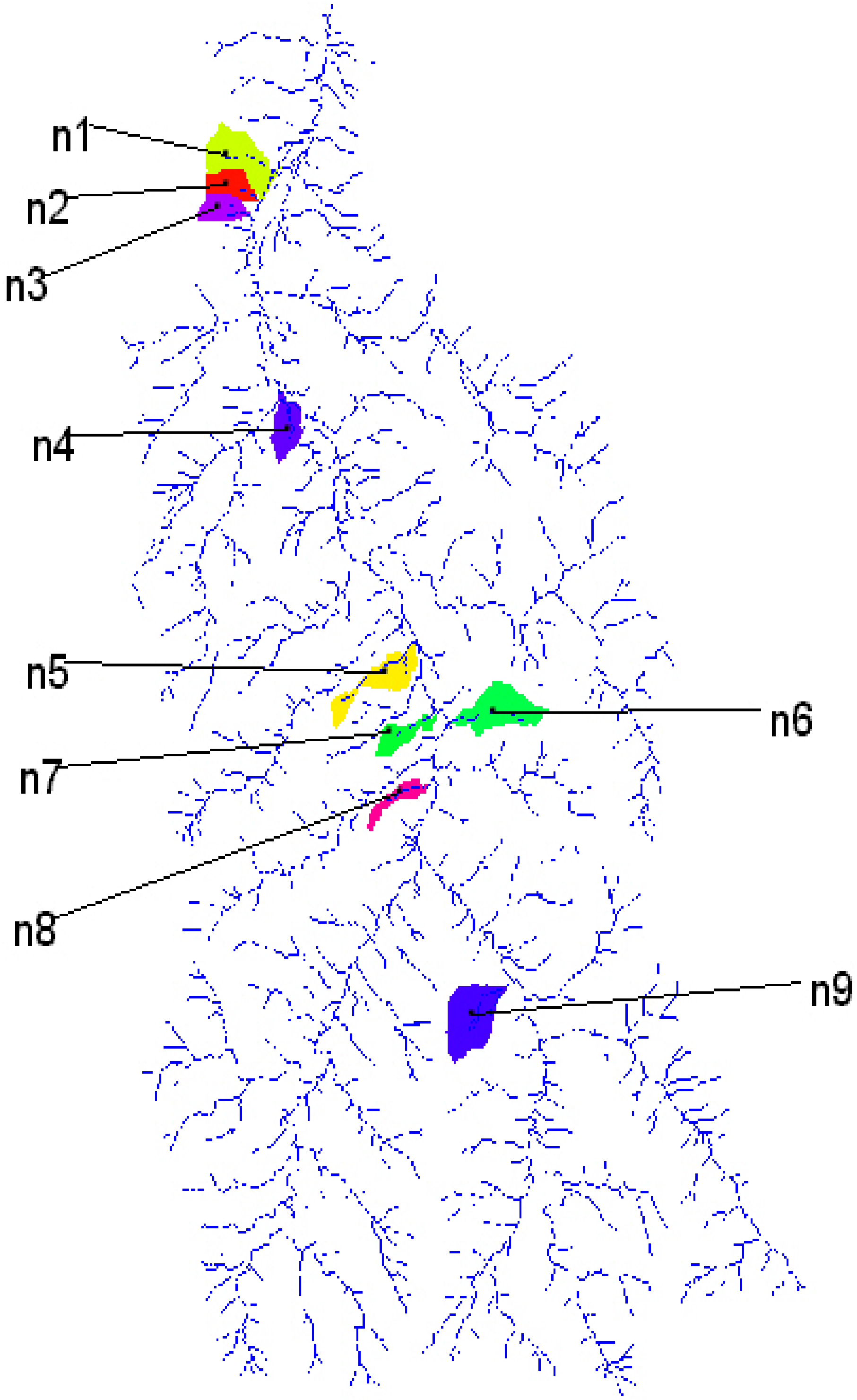


Figure 4. The 9 creeks classified in the group of lower susceptible for debris-flow initiation (non-potential debris flow)

3.2 Contributing factors of debris flow

Varnes [12] defined a debris avalanche as a very rapid to extremely rapid flow of predominantly coarse debris consisting of soil and/or weathered bedrock. Debris flow originates when poorly sorted debris (rock, soil, woody debris, etc.) is mobilized from hill slopes and channels by the addition of sufficient moisture. Landslides often yield debris flows downslope with a substantial increase in water content [13-15]. Zhou et al. [16] considered that debris-flow initiation needs three fundamental conditions and one of the four triggering conditions. The three fundamental conditions are abundant debris, a lot of water, and suitable slope. The four triggering conditions are heavy rainfall or snowmelt, highly variable topography, abrupt change in vegetation, and slope failure. Lin et al. [17] considered the initiation characteristics of debris flow in gravelly deposits as stream slope, rainfall, rainfall intensity, geological condition, grain size distribution, void ratio, shear strength, vegetation condition, and channeled topography. Lin et al. [6] also discussed the contributing factors of debris flow for the application of remote sensing and GIS.

Considering the above conditions, the most likely contributing factors of debris flow are topography, geology, and hydrology. Furthermore, the database can be further divided using 9 factors, including (1) rock formation, (2) fault length, (3) naked-land area, (4) slope of the watershed, (5) slope aspect of the watershed, (6) stream slope, (7) watershed area, (8) form factor, and (9) cover and management factor, C value.

The first three terms, rock formation, fault length, and naked-land area, can be consider as geological conditions. These factors influence the production of abundant debris.

The following three terms, slope of the watershed, slope aspect of the watershed, and stream slope, can be considered as topographic conditions. These factors will all have impact on the initiation and transportation of debris flow. Slope and slope aspect distributions of the watershed are raster-basis information data derived from DTM (digital terrain model) data. In this study, the size of grid cells is 40 m × 40 m. Stream slope represents the average slope declination of the stream.

The last three terms, watershed area, form factor, and C value, can be considered as hydraulic conditions. These factors, contributing greatly to peak flow rate of a stream, also affect on the initiation and transportation of debris flow. Form factor (F) is defined as [18]:

$$F=W/L_0=A/L_0^2 \tag{1}$$

where L_0= length of the river; W= average width of the watershed ($W=A/L_0$); and A = area of the watershed.

Form factor is also called basin shape. A larger form factor has rounder basin shape and larger peak flow rate [19].

Cover and management factor (C value) is taken from the plant-cover condition of the Universal Soil Loss Equation (USLE) [20]. C value ranges from zero to one. When the land is naked, C value is assigned with one. On the contrary, when the land is under a good vegetation condition, C value approaches to zero. C value varies with the vegetation type, season change, and the percentage of covered land.

3.3 Establishing the database of contributing factors

The first step in developing the database for a geographic information system (GIS) is to acquire the data and to place them into the system [21]. In Taiwan, many spatial data collected by governmental agencies, such as maps, aerial photographs, and other kinds of digital data, are available to the public. Table 1 shows the data types and data sources used in this paper.

Table 1. Types and sources of data used in this study

Data Type	Source	Precision	Publisher
• Topography	• Digital terrain model (DTM) • Terrain map • Basic aerial photography maps of Taiwan	• 40m X 40m • 1/25000 • 1/5000 or 10000	• Agriculture and Forestry Aerial Survey Institute • Information Center, Dept. of Land Administration • Agriculture and Forestry Aerial Survey Institute
• Geology	• The geological map of Taiwan • Basic aerial photography maps of Taiwan • SPOT image	• 1/250000 • 1/5000 or 10000 • 12.5m X 12.5m	• R.O.C Central Geological Survey • Agriculture and Forestry Aerial Survey Institute • Center for Space and Remote Sensing Research
• Hydrology	• Distribution map of hazardous debris flows─Nantou County • DTM • SPOT image	• 1/100000 • 40m X 40m • 12.5m X 12.5m	• Council of Agriculture • Agriculture and Forestry Aerial Survey Institute • Center for Space and Remote Sensing Research

The main preprocessing procedure of hydrologic data sets is to digitize the maps of terrain and to analyze the DTM Data of the watershed of Chen-Yu-Lan River through the WinGrid program. Figure 1 was obtained through these procedures.

In this paper, the DTM was a subset clipped from the DTM of Taiwan. The 40 m × 40 m DTM allows for relative comparisons of topography and slope aspect, but its resolution is not fine enough to process an accurate debris-flow simulation. Arc/Info (version 3.4.2) program, ArcView (version 3.2) program, and a GIS software WinGrid program for PC are used to process those data and calculate values of watershed area, form factor, and fault length. By using functions provided by the Spatial Analyst extension of ArcView, the elevation contours, the slope, and slope aspect can be derived. For example, Figures 5 and 6 show the maps of slope and slope aspect distributions in creek h1of the potential debris-flow watersheds in Chen-Yu-Lan River, and other creeks in the study can be analyzed in the same way. Tables 2 and 3 list the area of the slope and slope aspect of the 21 potential debris-flow watersheds.

The main preprocessing procedure of geological data sets includes digitizing the geological maps, establishing attribute, and error detection and correction. Figures 7 and 8 are the digital maps of rock formations and faults in the watershed of Chen-Yu-Lan River, and Table 4 is the area of different kinds of rock formations in the watershed of Chen-Yu-Lan River.

The data set of naked-land area and C value are acquired by WinGrid program to obtain the NDVI (Normalized Difference Vegetation Index) values, which can be transferred into C value of the USLE Equation, from SPOT satellite images (see Figure 9). C value, the cover and management factor in the USLE Equation, is inversely proportional to the NDVI value [22]. NDVI is one of the most widely used vegetation indices as [23]:

$$\text{NDVI}=\frac{IR-R}{IR+R} \tag{2}$$

where IR= infrared radiation value; R= red light radiation value.

Data sets of these 6 contributing factors (fault length, naked-land area, watershed area, form factor, stream slope, and C value) are acquired and shown on Table 5

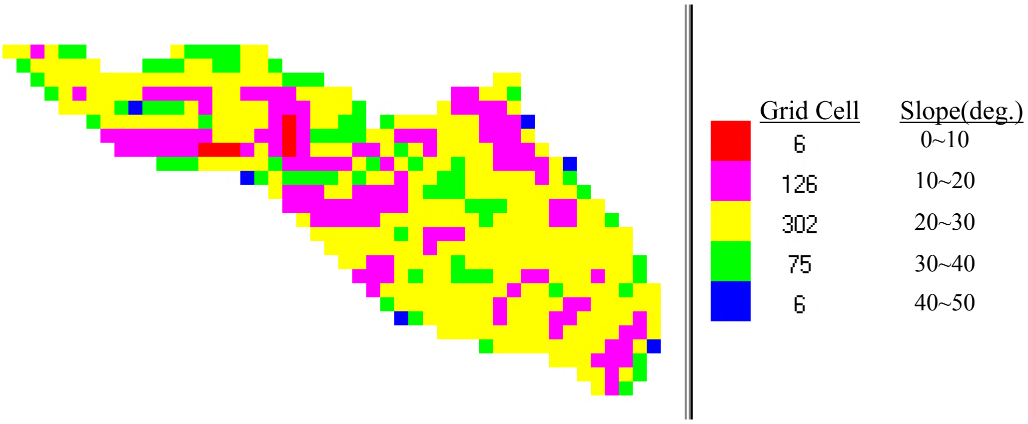


Figure 5. The spatial distributions of slope angles in the watershed of the h1 creek (cell size is 40m x 40m)

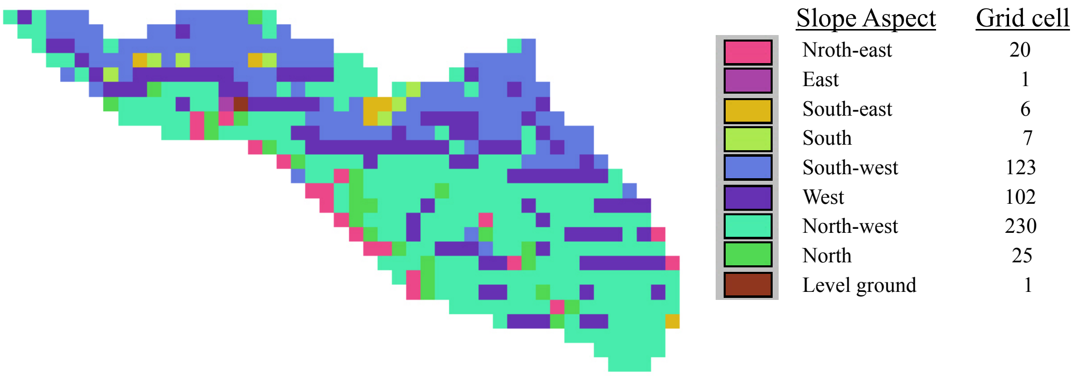
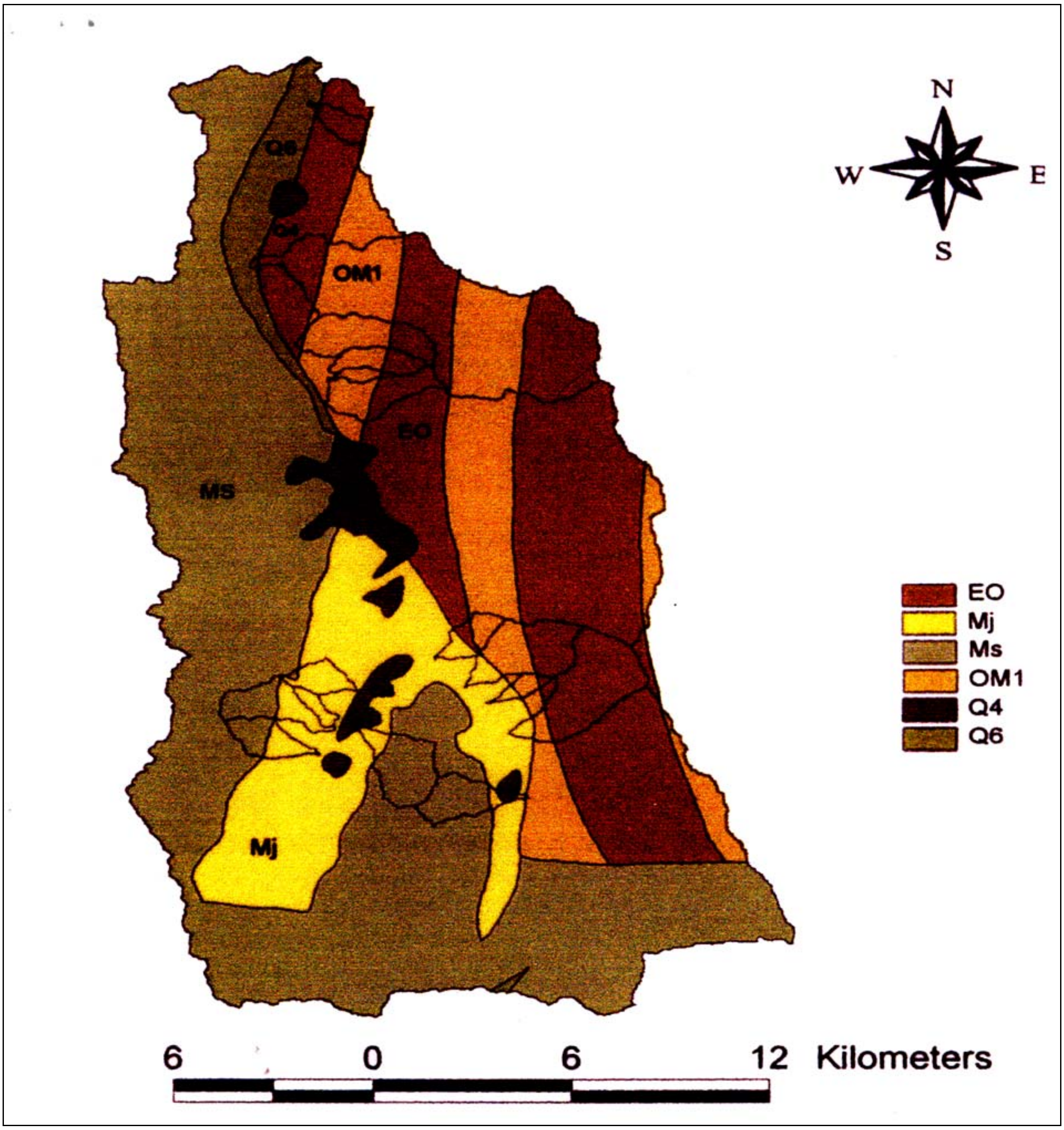


Figure 6. The spatial distributions of slope aspect in the watershed of the h1 creek (cell size is 40x40m)



(EO): Eocene to Oilgocene, Sileng Sandstone, Alternation, Slate, and Coal Shale.
(Mj): Middle Miocene, Ruifang Group, Sandstone, and Shale.
(Ms): Late Miocene, Sanxia Group, Sandstone, and Shale.
(OM1): Oligocene to Miocene, Gangou Formation, Argillite, Slate, and Phyllite.
(Q4): Pleistocene, Gravel, Soil and Sand.
(Q6): Modern Alluvium.

Figure 7. The overlapped rock formation map in the watersheds of the Chen-Yu Lan River

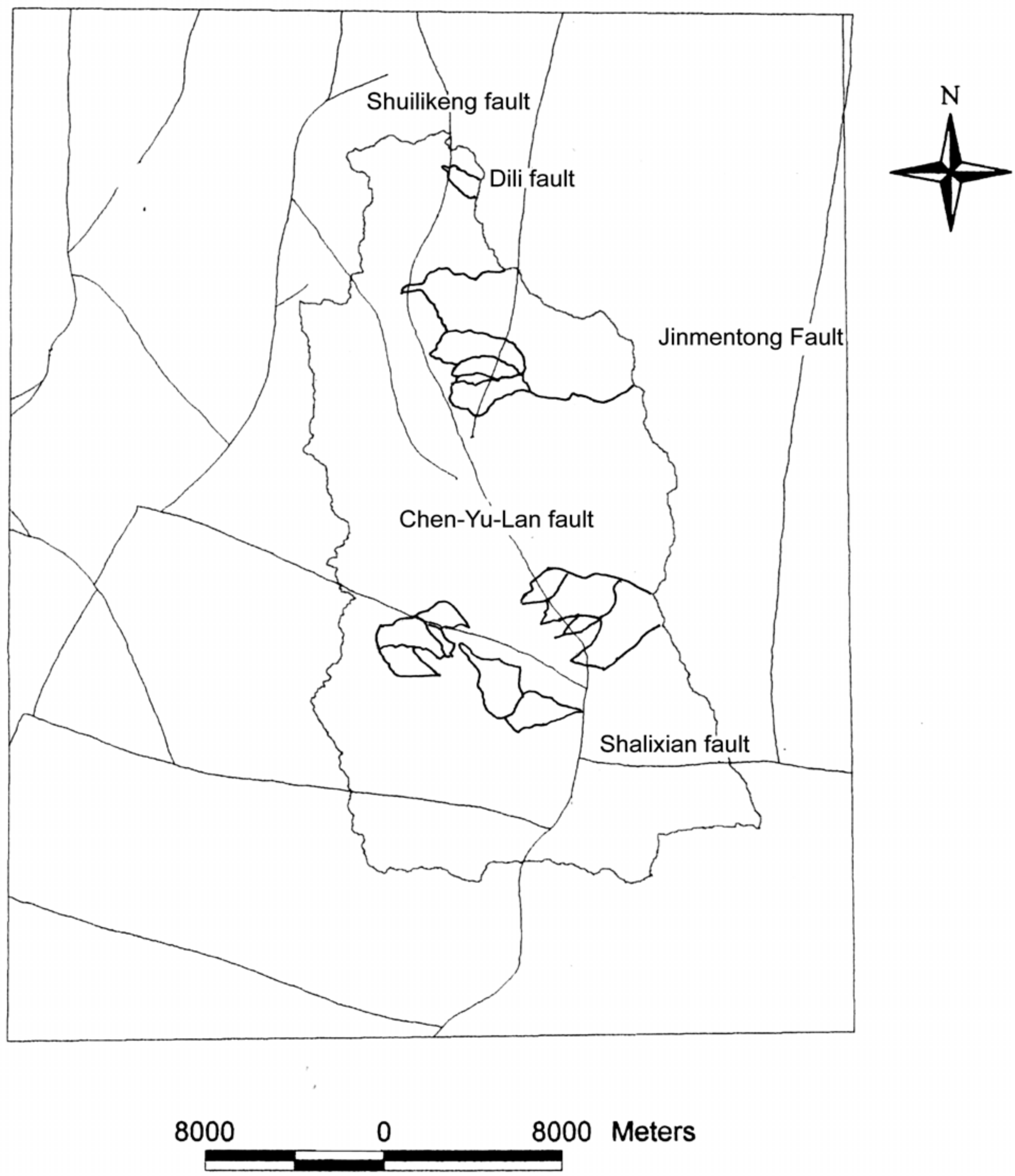


Figure 8. The overlapped fault map in the watersheds of the Chen-Yu-Lan River

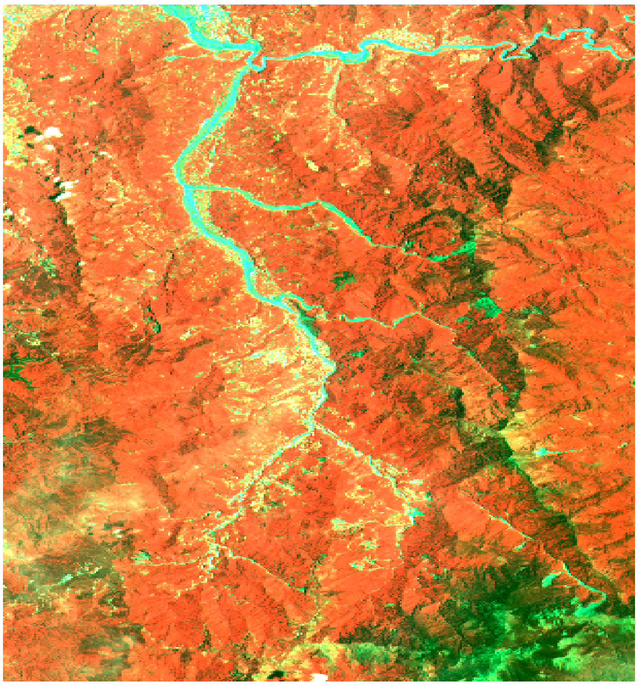


Figure 9. The SPOT satellite image of Chen-Yu-Lan River before Typhoon Herb (1996/6/5)

Table 2. The spatial distributions of slope angles in the watersheds of the 21 creeks investigated

Creek ID	0^o-10^o (ha.)	10^o-20^o (ha.)	20^o-30^o (ha.)	30^o-40^o (ha.)	40^o-50^o (ha.)	>50^o (ha.)
h1	0.96	12	48.32	20.16	0.96	0
h2	4	22.08	67.68	41.76	0.8	0
h3	1.76	14.72	37.12	22.88	4.32	0
h4	7.04	22.88	57.44	55.52	19.36	3.68
h5	1.76	19.2	59.2	91.2	30.24	0
h6	6.24	6.4	11.52	23.2	16.48	0.32
h7	69.28	27.04	72.96	132.16	62.88	0.16
h8	1.28	5.44	25.6	90.24	88.96	6.08
h9	1.28	12.8	36.96	88	42.08	6.72
h10	1.44	18.24	65.28	71.68	10.56	0
h11	3.04	16.48	51.52	118.08	51.52	2.88
h12	12.64	66.72	177.44	403.68	175.84	21.76
n1	11.84	19.84	56.8	68.64	30.56	6.08
n2	1.92	7.52	19.52	29.76	18.88	0.64
n3	0.8	7.68	19.36	31.04	21.12	0.48
n4	43.04	12.32	26.72	18.4	0	0
n5	76.96	24.16	29.28	17.92	2.08	0
n6	0.96	4.16	23.04	73.44	72.96	13.28
n7	39.52	11.84	22.88	5.12	0.32	0
n8	29.12	11.68	9.44	11.2	1.28	0
n9	0.32	30.88	58.72	93.12	35.04	2.56

Table 3. The spatial distributions of slope aspects in the watersheds of the 21 creeks investigated

Creek ID	North (ha.)	North-east (ha.)	East (ha.)	South-east (ha.)	South (ha.)	South-west (ha.)	West (ha.)	North-west (ha.)	Level ground (ha.)
h1	4	3.2	0.16	0.96	1.12	19.68	16.32	36.8	0.16
h2	11.36	13.28	21.44	0	0	0	43.84	44.96	1.44
h3	2.08	0.64	0.16	0	0.8	21.28	20.48	35.36	0
h4	0.64	0.64	0	9.44	5.28	50.56	55.36	44	0
h5	24.16	41.28	23.68	0	0	0	35.36	76.48	0.64
h6	3.36	30.88	10.4	0	0	0	11.68	7.52	0.32
h7	44	121.6	78.24	0	0	0	54.72	59.36	6.56
h8	0.32	0.48	1.28	19.04	14.24	71.84	75.2	34.88	0.32
h9	66.88	31.68	13.12	0	0	0	32.48	41.76	1.92
h10	26.56	25.76	19.36	0	0	0	21.12	73.76	0.64
h11	48.8	75.52	50.72	0	0	0	27.68	39.36	1.44
h12	65.12	176.32	19.52	15.04	14.88	232.8	108.64	225.12	0.64
n1	8.32	49.92	31.36	67.68	12.96	16.32	2.24	4.32	0.64
n2	0.8	19.04	14.88	33.92	3.68	5.76	0	0.16	0
n3	0.64	17.92	17.44	38.72	2.24	3.04	0	0.48	0
n4	15.04	39.36	18.08	1.12	0.64	1.12	7.2	17.44	0.48
n5	14.88	75.2	25.28	13.92	1.28	0.8	3.36	14.88	0.8
n6	3.2	2.88	0.64	3.36	7.52	88.64	41.76	39.68	0.16
n7	9.6	38.72	16	10.4	0.64	0.16	0.48	3.52	0.16
n8	4.32	27.36	14.08	5.28	0.64	0.16	0.16	10.72	0
n9	23.36	113.28	28.96	33.92	0	0	0.48	20.64	0

Table 4. The spatial distributions of rock formation in the watersheds of the 21 creeks investigated

Creek ID	geo EO 〔ha.〕	geo OM1 〔ha.〕	geo Mj 〔ha.〕	geo Ms 〔ha.〕	geo Q4 〔ha.〕	geo Q6 〔ha.〕
h1	76.76	0.33	0	0	0	5.29
h2	132.50	0	0	0	0	3.82
h3	77.86	0	0	0	0	2.49
h4	114.56	48.91	0	0	2.44	0
h5	87.92	113.68	0	0	0	0
h6	8.42	55.74	0	0	0	0
h7	192.01	172.47	0	0	0	0
h8	216.53	0.52	0	0	0	0
h9	36.07	89.40	62.37	0	0	0
h10	0	0	159.30	7.90	0	0
h11	0	0	110.40	133.12	0	0
h12	0	0	164.71	693.68	0	0
n1	0	0	0	143.25	0	49.92
n2	0	0	0	69.22	0	9.48
n3	0	0	0	74.66	0	5.52
n4	6.57	0	0	47.63	0	46.12
n5	42.04	0	11.5	26.26	70.38	0
n6	32.47	155.17	0	0	0	0
n7	3.38	0	41.13	0	35.01	0
n8	0	0	29.76	0	32.28	0
n9	0	0	74.93	145.64	0	0

Note: (geo EO): Eocene to Oilgocene, Sileng Sandstone, Alternation, Slate, and Coal Shale.
(geo Mj): Middle Miocene, Ruifang Group, Sandstone, and Shale.
(geo Ms): Late Miocene, Sanxia Group, Sandstone, and Shale.
(geo OM1): Oligocene to Miocene, Gangou Formation, Argillite, Slate, and Phyllite.

(geo Q4): Pleistocene, Gravel, Soil and Sand.
(geo Q6): Modern Alluvium.

Table 5. Data of the six factors in the watersheds of the 21 creeks investigated

Creek ID	Watershed area (ha.)	Form factor	Stream slope (deg.)	Naked-land area (ha.)	Fault length (m)	C value
h1	0.82	0.35	26.25	69	245	0.0931
h2	1.36	1.46	26.15	94	483	0.1052
h3	0.81	0.51	27.23	56	416	0.1139
h4	1.66	0.50	30.11	114	47	0.1258
h5	2.02	0.38	31.84	176	904	0.124
h6	0.64	0.13	32.04	55	243	0.0987
h7	3.64	21.71	28.59	284	1771	0.1088
h8	2.18	0.45	38.41	158	0	0.1282
h9	1.88	0.39	35.28	147	1191	0.094
h10	1.67	0.29	29.4	108	1396	0.1163
h11	2.44	0.23	34.18	183	0	0.1128
h12	8.58	0.24	34.55	617	1708	0.0932
n1	1.94	0.54	31.61	160	0	0.0992
n2	0.78	1.02	33.56	73	0	0.1058
n3	0.80	1.50	34.05	68	0	0.1297
n4	1.00	0.31	16.90	52	572	0.1698
n5	1.50	0.18	14.41	68	848	0.0770
n6	1.88	0.33	39.53	128	0	0.1008
n7	0.80	0.41	14.79	43	200	0.1032
n8	0.63	0.26	17.20	28	0	0.0719
n9	2.21	0.62	32.07	181	1180	0.1060

4. Multivariate analysis results

In this paper, the above 9 contributing factors, with different units and different scales, are obtained in 27 indexes. These indexes of the contributing factors are analyzed by multivariate analysis procedures. The principal components analysis (PCA) and discriminant function analysis (DA) are used in this study. Principal components analysis is a statistical technique applied to a single set of variables to discover which sets of variables in the set form coherent subsets that are relatively independent of one another. Variables that are correlated with one another which are also largely independent of other subsets of variables are combined into factors. The generated factors are thought to be representative of the underlying processes that have created the correlations among variables.

Through the principal components analysis operation, the matrix of eigenvectors for the first to fifth principal components (see Table 6), the eigenvalue, variance, and total system variance of the 27 principal components (see Table 7) can be calculated by SPSS software. The number of significant principal components is determined using Kaiser's rule [24]. According to Kaiser, eigenvalues greater than 1 are significant when the number of observations are small or moderate. Table 7 has shown that the first five components out of the total 27 are extracted and 87.20 % of the total system variance can be explained.

Table 6. Matrix of eigenvector for the 27 indexes of the 9 factors from the first to fifth principal component

Indexes	The first principal Component (factor loadings)	The second principal Component (factor loadings)	The third principal Component (factor loadings)	The fourth principal Component (factor loadings)	The fifth principal Component (factor loadings)
Watershed area	0.9966	0.0720	0.0013	-0.0181	-0.0269
Form factor	-0.0403	0.1184	-0.0327	-0.0176	0.9119
Stream slope	0.0910	0.1833	-0.2051	-0.8057	-0.1712
Naked-land area	0.9923	0.0743	0.0167	-0.0068	-0.0130
Fault Length	0.7569	0.1254	-0.1034	0.0346	0.2857
C Value	0.0540	-0.2238	0.4369	-0.4769	0.2601
North	0.9828	-0.0924	-0.0529	-0.0006	-0.0563
North-East	0.9928	-0.0307	0.0022	0.0440	-0.0149
East	0.9652	-0.1305	0.0109	0.0201	0.0694
South-East	-0.1055	0.2496	0.7380	0.0829	-0.1671
South	-0.0206	0.6540	0.5510	-0.1089	-0.2113
South-West	0.0519	0.8402	0.1246	-0.0957	-0.0965
West	0.9140	0.1387	-0.0481	-0.1563	-0.0042
North-West	0.9362	0.1593	-0.0985	-0.0828	-0.0058
Level Ground	0.9455	-0.1207	0.0011	0.0229	0.1673
Zero to Ten Deg.	0.8987	-0.1081	0.1579	0.3907	0.1244
Ten to Twenty Deg.	0.9882	0.1003	0.0376	0.0987	0.0114
Twenty to Thirty Deg.	0.9847	0.0389	0.0200	-0.0013	0.0001
Thirty to Forty Deg.	0.9726	0.1382	-0.0381	-0.0724	-0.0112
Fourty to Fifty Deg.	0.9669	0.0407	-0.0165	-0.1023	-0.1104
Over Fifty Deg.	0.9475	0.0666	0.0175	-0.0751	-0.1911
geo EO	0.9345	-0.2289	0.0142	-0.0923	-0.1041
geo OM1	0.9477	-0.1976	0.0219	-0.0080	-0.0433
geo MJ	-0.0496	0.5877	-0.4596	-0.0365	0.0429
geo MS	0.0469	0.9144	0.0214	0.0538	0.1832
geo Q4	0.0059	0.0314	-0.0397	0.9295	-0.0849
geo Q6	0.0048	-0.0412	0.8587	0.0185	0.0823

Table 7. The eigenvalues and variances of the 27 principal components

Order of principal components	Eigenvalue	Variance(%) (percent trace)	Total system variance (%) (cumulative percent)
1st	15.46	57.26	57.26
2nd	3.04	11.26	68.52
3rd	2.10	7.79	76.32
4th	1.78	6.60	82.92
5th	1.16	4.29	87.20
6th	0.97	3.60	90.80
7th	0.85	3.15	93.94
8th	0.47	1.76	95.70
9th	0.39	1.43	97.13
10th	0.28	1.03	98.16
11th	0.17	0.63	98.79
12th	0.12	0.43	99.22
13th	0.09	0.34	99.56
14th	0.05	0.18	99.74
15th	0.03	0.10	99.84
16th	0.02	0.06	99.90
17th	0.01	0.04	99.93
18th	0.01	0.03	99.96
19th	0.01	0.02	99.98
20th	0.00	0.01	99.99
21st	0.00	0.01	100.00
22nd	0.00	0.00	100.00
23rd	0.00	0.00	100.00
24th	0.00	0.00	100.00
25th	0.00	0.00	100.00
26th	0.00	0.00	100.00
27th	0.00	0.00	100.00

Discriminant function analysis (DA) is used to classify cases into the values of a categorical dependent, usually a dichotomy. If discriminant function analysis is effective for a set of data, the classification table of correct and incorrect estimates will yield a high percentage correct. The discriminant function is established through discriminant analysis by Fisher's method for these five principal components, the debris-flow discriminant function for a specific creek is obtained here as:

$$\begin{aligned} z = &-6.636x_1 + 1.142x_2 + 0.76x_3 \\ &+ 0.843x_4 + 0.625x_5 - 2.016 \end{aligned} \tag{3}$$

where z = discriminant score (DA score or Z score); x_1 to x_5= discriminating variables of the first principal component to the fifth principal component.

Table 8 has shown the discriminating variables of the first principal component to the fifth principal component (x_1 to x_5) and DA scores for the 21 creeks investigated in this research. Following the mentioned processes, any creek in the watershed of Chen-Yu-Lan River can be grouped into two categories. One is the group of potential debris flow (higher susceptible for debris-flow initiations) when the DA scores are lower than the cutoff in these creeks. The other is the group of none-potential debris flow (lower susceptible for debris-flow initiations) when DA scores are higher than the cutoff in these creeks. The cutoff of the DA score for potential or none-potential debris flow is 0.33 in this research. Table 9 and 10 has shown the results and efficiency of the discriminant analysis in the 21 creeks investigated. Comparing the results obtained from the initial groups (12 potential debris flow and 9 none-potential debris flow) defined by field investigation, and the classified groups (14 potential debris flow and 7 none-potential debris flow) evaluated by the discriminant analysis, we found that the total correct percentage of the discriminant analysis is as high as 90.5%.

Table 8. The discriminating variables of the first to fifth principal components (x_1 to x_5) for the 21 creeks investigated

Creek ID	X_1	X_2	X_3	X_4	X_5	DA score (Z)
h1	-0.4235	-0.41898	-0.09015	0.1653	-0.33229	0.179096
h2	-0.26657	-0.64184	-0.10356	0.01611	0.18007	-0.93241
h3	-0.40943	-0.50699	-0.0107	-0.15556	-0.04549	-0.04552
h4	-0.29347	-0.06636	0.47946	-0.46339	-0.41182	-0.42789
h5	-0.16946	-0.66299	-0.15361	-0.56376	0.135	-2.15606
h6	-0.44125	-0.626	-0.36864	-0.19395	-0.36242	-0.47288
h7	0.27603	-0.44076	-0.11678	0.01908	4.27223	-1.75211
h8	-0.2566	0.59333	1.0705	-1.226	-1.03149	-0.50032
h9	-0.17355	-0.18707	-0.85508	-0.37135	-0.1757	-2.15065
h10	-0.25085	0.1878	-0.9926	-0.25022	0.37074	-0.87023
h11	-0.2245	0.16353	-0.78596	-0.48807	-0.09739	-1.40901
h12	0.59413	4.67179	-0.21479	-0.30822	-0.42558	-1.3126
n1	-0.33401	0.61965	3.55255	0.00496	-0.75759	3.138902
n2	-0.49229	-0.14239	0.95493	-0.29208	-0.46168	1.279338
n3	-0.48958	-0.30756	1.10526	-0.60579	-0.12352	1.134006
n4	-0.33349	-1.09703	2.35274	-0.01037	1.33875	1.561051
n5	-0.22821	-0.17947	-0.06748	3.713	-0.40301	2.120213
n6	-0.28731	0.43551	0.06424	-0.88394	-1.11071	-1.00277
n7	-0.42059	-0.41434	0.0106	2.05585	-0.1294	1.962211
n8	-0.46657	-0.31174	-0.44714	2.15816	-0.59962	1.828801
n9	-0.23476	0.30466	0.01903	-0.08849	-0.00161	-0.17118

Table 9. The results of the discriminant analysis in the 21 creeks investigated

Creek ID	Intial group	Glassfied group	Discriminant score (z)
h1	P	P	0.179096
h2	P	P	-0.93241
h3	P	P	-0.04552
h4	P	P	-0.42789
h5	P	P	-2.15606
h6	P	P	-0.47288
h7	P	P	-1.75211
h8	P	P	-0.50032
h9	P	P	-2.15065
h10	P	P	-0.87023
h11	P	P	-1.40901
h12	P	P	-1.3126
n1	NP	NP	3.138902
n2	NP	NP	1.279338
n3	NP	NP	1.134006
n4	NP	NP	1.561051
n5	NP	NP	2.120213
n6	NP	P	-1.00277
n7	NP	NP	1.962211
n8	NP	NP	1.828801
n9	NP	P	-0.17118

Note: 1.Group P is group of potential debris flows
2.Group NP is group of none-potential debris flows

Table 10. The efficiency of the discriminant analysis in the 21 creeks investigated

GROUP	No. of Classified Group NP	No. of Classified Group P	Total Number	Correct Percent %	Incorrect Percent %
Initial Group NP	7	2	9	77.78	22.22
Initial Group P	0	12	12	100	0

Finally, hazard assessment of potential debris flows can be estimated based on DA scores assumed the DA scores are normal distribution. In our study, the DA scores have been grouped according to the appeared probability finally into four classes: (a) DA score≦-1.34, high hazard of potential debris flow; (b) –1.34< DA score≦-0.64, moderate hazard of potential debris flow; (c) –0.64< DA score≦0.33, low hazard of potential debris flow; (d) 0.33< DA score, none-potential debris flow.

According to the map of the Council of Agriculture, R.O.C., in 1996, there were 16 creeks of Chen-Yu-Lan River determined to have potential debris-flow hazards based on evaluation of the average stream slope, watershed area, and protective object [2]. Figure 10 shows the watershed locations of the 16 potential debris flows along the Chen-Yu-Lan River. These 16 creeks are selected for hazard assessment of potential debris flow in this research to test the applicability of this hazard assessment approach. The analytical results show that all the DA scores are lower than 0.33 in these 16 creeks. All these 16 creeks of Chen-Yu-Lan River determined to have potential debris-flow hazards (see Table 11). According to the above rules, these 16 potential debris flows are grouped into high hazard (9 creeks, creeks 26, 27, 28, 30, 31, 32, 34, 37, and 38), moderate hazard (5 creeks, creeks 25, 33, 35, 36, and 40), and low hazard (2 creeks, creek 29 and 39).

5. Disscusion and conclusions

From July 31st through August 1st in 1996, the heavy rainfall brought by Typhoon Herb triggered several debris flows in the watershed of the Chen-Yu-Lan River. Comparing the records of debris flows during Typhoon Herb with the qualitative analytical results, it is found that debris flow took place in eight of the mentioned 16 potential debris flows occurred during Typhoon Herb. These eight creek channels of debris flow are creeks 25, 26, 28, 29, 30, 31, 37, and 40. Among these creeks, the creek 29 is evaluated as low hazard, the creeks 25 and 40 are as moderate hazard, and others (creeks 26, 28, 30, 31,and 37) are as high hazard. The results suggest that the hazard assessment method developed in this study may reveal the potential hazard of debris flows in the watershed of Chen-Yu-Lan River. This hazard assessment method could be applied to other watersheds of river systems in Taiwan. Other conclusions include:

1. By utilizing the capability of spatial analysis provided in GIS software, the watershed factors are calculated and served as contributing factors. In this study, GIS technology offers a useful tool for hazard assessment of potential debris flows.
2. The database of topography, geology and hydrology are grouped into 9 factors as the contributing factors of debris-flow initiation, including: (1) rock formation, (2) fault length, (3) naked-land area, (4) slope of the watershed, (5) slope aspect of the watershed, (6) stream slope, (7) watershed area, (8) form factor, and (9)

cover and management factor, C value. However, the contributing factors are not limited to these 9 items, whether additional contributing factors should be added to the assessment processes depends on the advances in understanding the mechanism of debris flow.

3. Multivariate analysis can be applied to analyze the contributing factors for debris-flow occurrence and assess hazards associated with debris flows. The principal components analysis and discriminant function analysis are used in this study. Through the principal components analysis operation, the first five components out of the total 27 are extracted and 87.20 % of the total system variance can be explained. Comparing the results obtained from the initial groups defined by field investigation and those by the classified groups evaluated by the discriminant analysis, we found that the total correct percentage of the discriminant analysis can be as high as 90.5%.

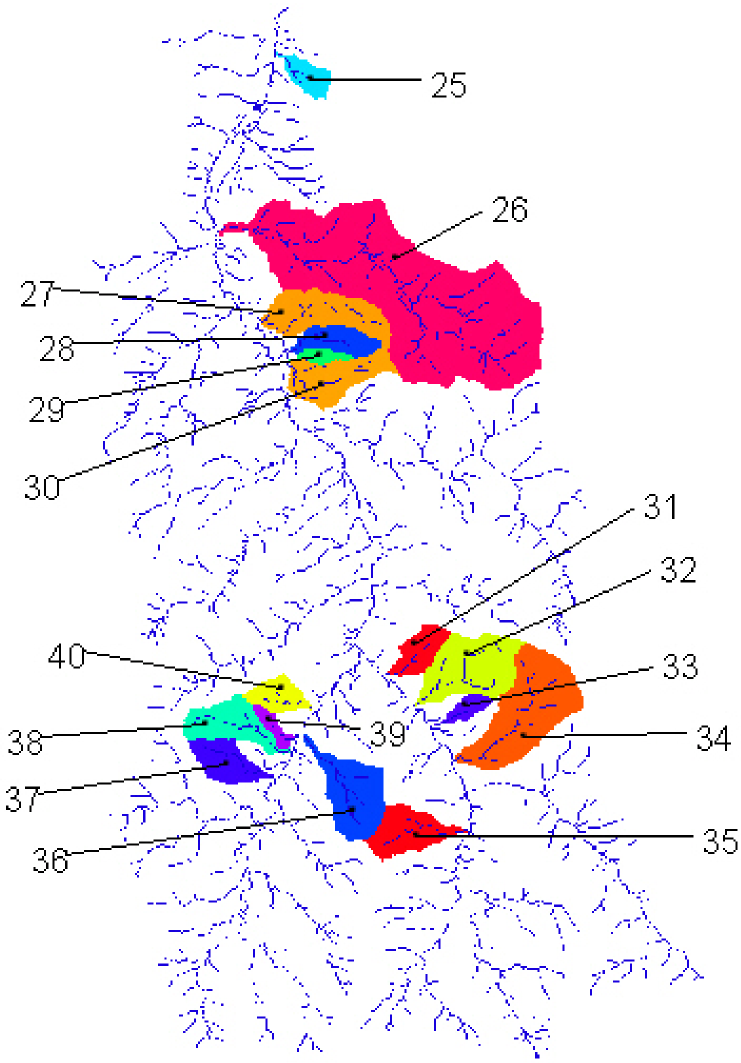


Figure 10. The 16 creeks of Chen-Yu-Lan River determined to have potential debris-flow hazards by Council of Agriculture, R.O.C., in 1996

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References

[1] Council of Agriculture, Republic of China, 1996. *The Map of Hazardous Debris-Flow Streams in Taiwan*, Scale: 1/250,000 (in Chinese).

[2] Shieh, C. L.and Jiang J. H. 1992. Study on the judgment of dangerous valley of debris flow, *Proceedings of Chinese 6th Conference on Hydraulic Engineering:* 262-273.

[3] Gupta, B. P. and Joshi, B. C. 1990. Landslide hazard zoning using the GIS approach - a case study from Ramganga Catchment, Himalayas, *Engineering Geology*, 28: 119-131.

[4] Lin, M. L. and Jeng S. S. 1995. A preliminary study of risk assessment of debris flow using GIS, *Journal of the Chinese Institute of Civil and Hydraulic Engineering,* 7, 4: 475-486.

[5] Cheng, K. Y., Lin, L. K., and Chang, S. Y. 1997. The filed investigation and GIS application in a potential hazardous area of debris flow, *Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment, Proceedings of First International Conference,* ASCE: 83-92.

[6] Lin, J. Y., Yang, M. D., and Lin, P. S. 1998. An evaluation on the applications of remote sensing and GIS in the estimation system on potential debris flow, *1998 Annual Conference of Chinese Geographic Information Society*, (CD edition).

[7] Lin P. S., Lin J. Y., Hung J. C., and Yang M.D. 2000. Risk Assessment of Potential Debris Flows using GIS, *Proceedings of the Second International Conference on Debris-Flow,* Balkem: 431-440.

[8] Benda, L. and Cundy, T. 1990. Predicting deposition of debris flows in mountain channels, *Canadian Geotechnical Journal,* 27: 409-417.

[9] Auer, K. and Shakoor, A. 1993. A statistical approach to evaluate debris avalanche activity in central Viginia, *Engineering Geology,* 33: 305-321.

[10] Cheng, J. D., Wu, H. L., and Chen, L. J. 1997. A comprehensive debris-flow hazards mitigation program in Taiwan, *Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment, Proceedings of First International Conference,* ASCE: 93-102.

[11] Nakagawa, H. and Takahashi, T. 1997. Estimation of a debris-flow hydrograph and hazard area, *Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment, Proceedings of First International Conference,* ASCE: 64-73.

[12] Varnes, D. J. 1978. Slope Movement Types and Processes. In: Schuster R. L. and Krizek R. J. (Eds), *Landslide, Analysis, and Control.* National Academy Science Transportation Research Board Spec. Report, 176: 11-33.

[13] Baily, R. G. 1971. "*Landslide hazards related to land use planning in Teton National Forest, northwest Wyoming. Ogden, Utah*: *USDA Forest Service Intermountain Region*", 131 pp.

[14] Burroughs, E. R., Chalfant, G., and Townsed, M. A. 1976. "*Slope stability in road construction. Porland, Oregon: Bureau of Land Management*", Oregon State Office, 102 pp.

[15] Liaw, W. M., Chou H. T., and Lin M. L. 1999. A case study of debris flow induced by landslide, *Journal of Chinese Soil & Water Conservation* 30, 2: 157-165.

[16] Zhou, B. F., Lee, D. J., Luo, D. F., Lu, R. R., and Yang, C. S. 1991. "*A Guide for Debris-flows Hazard Mitigation*", Science Publisher Co. Ltd., Beijing: 4-5 (in Chinese).

[17] Lin, P. S., Feng, T. Y., and Lee, C. M. 1993. A study on the initiation characteristics of debris flow in gravelly deposits, *Journal of Chinese Soil and Water Conservation,* 24, 1: 55-64.

[18] Wang, R. Y. and Yea R. 1979. "*Hydrology*", National Edition Center, Taiwan 133 pp.

[19] Wohl, E. E. and Pearthree P. P. 1991. Debris flows as geomorphic agents in the Huachuca Mountains of Southeastern Arizona, *Journal of Geomorphology,* 4: 273-292.

[20] Council of Agriculture, Republic of China, 1992. "*Handbook of Soil and Water Conservation, Taiwan*": 1-156 - 1-170 (in Chinese).

[21] Star J. and Estes J. 1990. "*Geographic Information Systems- an Introduction*", Prentice Hall.

[22] Lin, C. Y. and Lin, W. T. 1999. An automatic delineation of slope length factor for watershed soil loss estimation, *Journal of Chinese Soil and Water Conservation,* 30, 4: 313-320.

[23] Campbell J. B. 1987. "*Introduction to REMOTE SENSING*", The Guilford Press, New York, 384-387.

[24] Kaiser, H. F. 1960. The Application of electronic computers to factor analysis, *Educational and Psychological Measurement*, 20: 141-151.