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Potential Hazard Map for Disaster Prevention Using GIS-Based Linear Combination Approach and Analytic Hierarchy Method

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ABSTRACT

In recent years, global warming has gradually become obvious, thus created the climate change. Typhoon Morakot attacked Taiwan and brought heavy rainfall in August, 2009. In mountainous areas including Central and South Taiwan, the flood and debris flow disasters were induced by the typhoon. In this study, Changhua City is selected as the research region and the Delphi method is employed to interview experts and establish comprehensive evaluation criteria for assessing the evacuation plan on disaster areas. The concept is to combine the landslide potential analysis by geographic information systems with the flood or debris flow maps into the potential hazard map. Meanwhile, analytic hierarchy method (AHP) is comprehensively carried on the expert questionnaire survey for the potential hazard map of the compound disaster states. It should be useful for the local government and native people in the future.

Keywords: Geographic Information Systems; Potential Hazard Map; Analytic Hierarchy Method (AHP)

1. Introduction

With the gradually apparent global warming causing the climate change, Typhoon Morakot attacked the central and southern Taiwan in August 2009 and resulted in serious disasters. With the unusual route of Typhoon Morakot, its long stay in Taiwan, and the effect of southwest monsoon, the heavy rainfall caused major disasters. According to the estimation of Water Resources Agency [1], the rainfall reached the world extreme record. Besides, regarding the historical rainfall in one day, Typhoon Morakot was also ranked at the top. Climate change resulted from global warming is expected to result in similar events in the future. The entire Taiwan experienced such heavy rainfall during the attack of Typhoon Morakot that various disasters were caused by long-period, high-intensity, and wide-spread rainfall, such as floods, debris flows, landslides, and landslide-dammed lakes [2,3].

In face of the reflection on natural disasters and disaster relief operations as well as in corresponding to the change of climate and natural environment, a lot of thinking models should be adjusted. How to arrange secure and prompt evacuation points has therefore become one of the primary research issues. A multi-criteria evaluation (MCE) method can usually deal with the available information concerning choice-possibilities in regional planning. Meanwhile, weighted linear combination (WLC) is one of the widely employed MCE methods for land suitability analysis [4]. Besides, flood risk and flood damage estimates are studied by spatial multi-criteria analysis, geographic information systems (GIS) and mathematical models [5-8]. The previous researches offered the knowledge of flood risk in different spatial locations for developing effective flood mitigation strategy and damage estimation for a watershed or regional planning.

Therefore, with analytic hierarchy process (AHP) to proceed expert questionnaire survey and to analyze the weight of various factors, this study aims to collect map data related to landslide, flood potential analysis, debris flow potential areas, and land use in Changhua City. The map overlaying analysis in geographic information systems (GIS) is utilized for establishing the compound potential hazard map. The research outcomes are expected to provide the relevant sectors evaluating the original hideout points, evacuation routes or evacuation system, and disaster prevention.

2. Research Method

With linear combination method to evaluate the compound potential hazard map, the combination would give

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each factor a relative weight when evaluating the appropriateness of factor attribute toward the evaluated subject. Analytic hierarchy process (AHP) was applied to designing the expert questionnaire for the weights of factors. With pair wise comparison to estimate the eigenvector for the weight of the criteria [9], the weight was directly evaluated by the map overlaying analysis in geographic information systems (GIS). AHP and the map overlaying in GIS are briefly described as follows.

2.1. Analytic Hierarchy Process (AHP)

Analytic hierarchy process (AHP) could master the factors in decision-making with hierarchic structures. The nominal scale is applied to pair comparison among factors so that the uncountable human feelings and preference are quantified and the pair comparison matrix is established for the eigenvector for the priority. It presents the characteristics of structure, complex scale, rational pair comparison, and integrating opinions from different decision-makers with the weighted average value. Since Saaty first proposed AHP in 1971 and published the introduction in 1980, the book was revised in 1986 and AHP has been widely applied to decision analysis practices.

In order to obtain the relative importance of factors, they are paired for comparison. According to the suggestion of Saaty of nine-scale (**Table 1**), it could be designed a paired questionnaire. When there are n criteria, $n(n-1)/2$ times pair comparisons are required, **Table 2**. The compared results are established paired positive reciprocal matrices, where a_{ij} is the compared value between i and j, and the main diagonal is the self-comparison of factors that the value appears 1. The compared questionnaire becomes the value on the top-right of the diagonal in the matrix, while the value on the bottom-left of the diagonal is the reciprocal, *i.e.*, $a_{ji} = 1/a_{ij}$. When pair evaluation is preceded, the entire geometric mean is regarded as the representative. The pair matrix **A** is shown as below:

$$\mathbf{A} = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ a_{21} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ a_{n1} & a_{n2} & \cdots & 1 \end{bmatrix} = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix} \quad (1)$$

For the relative weight among factors, the eigenvalue solution in numerical analyses could be utilized for the maximum eigenvalue and the correspondent eigenvector.

According to AHP, pair comparison should satisfy the transitivity of preference and strength. Nevertheless, the actual evaluation could hardly satisfy such a hypothesis. Saaty therefore considered consistency tests for pair evaluation, including the steps of

1) Calculating Consistency Index (*C.I.*)

$$C.I. = \frac{\lambda_{\max} - n}{n-1}; \quad (2)$$

2) Calculation Consistency Ratio (*C.R.*)

$$C.R. = \frac{C.I.}{R.I.}, \quad (3)$$

where $\lambda_{\max}$ is the maximum eigenvalue of the matrix, n is the matrix rank, and *R.I.* (Random Index) is the consistency index of the random matrix. *R.I.* value is related to the matrix level that the correspondent *R.I.* values could be found on the matrix level (**Table 3**).

Saaty [10] regarded the comparison being randomly generated when *C.R.* approached 1 and the consistency being higher when *C.R.* approached 0. In general, $C.R. \le 0.1$ was considered acceptable, while $C.R. > 0.1$ showed the inconsistency that they had to be re-compared. After calculating the weight among factors in the hierarchies, the weight of the overall hierarchy should also be calculated.

2.2. Map Overlaying Analysis in Geographic Information Systems

Map overlaying is regarded as the major operation in analyzing the environmental features for regional planning [11]. Basically, it classifies various environmental factors by space distribution characteristics and proceeds overlaying with evaluations. When computer technology was rapidly progressed in 1970s, it gradually replaced manually map overlaying and reduced time consuming and human errors. Geographic information systems developed for distinct purposes rapidly grew in 1980s that the map overlaying analysis became one of the functions

Table 1. The meaning and description of scales for pair comparison with AHP (source: Saaty, 1990 [10]).

Scale	Definition	Description
1	Equally important	The contribution of the two factors is equally important.
3	Slightly important	Experiences and judgment slightly tend to certain factor.
5	Quite important	Experiences and judgment strongly tend to certain factor.
7	Extremely important	Experiences and judgment extremely strongly tend to certain factor.
9	Absolutely important	There is sufficient evidence for absolutely tending to certain factor.
2,4,6,8	The median between two neighboring scales	In between two judgments

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Table 2. Questionnaire example of pair comparison in AHP.

	More important on the left																More important on the right	
	Extent																Extent	
	Absolutely important		Extremely important		Quite important		Slightly important		Equally important		Slightly important		Quite important		Extremely important		Absolutely important	
	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	
A																		B

Table 3. Random Index value (source: Saaty, 1990 [10]).

Rank	1	2	3	4	5	6	7	8	9	10
R.I.	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

in geographic information systems [12,13]. After the expert questionnaire survey and AHP for weight of attributes, the maps collected by the map overlaying in GIS were overlaid for evaluations. The weighted linear combination analysis [4] was applied using the following equation:

$$E.R. = \sum w_i x_i \,, \quad (4)$$

where *E.R.* is the environmental risk, w_i is a weighting factor *i* which is decided by AHP, and x_i is the criterion score of factor *i*. The next section will illustrate the score estimations of each factor *i* and application of potential hazard map overlaying in geographic information systems in details.

3. Results and Discussions

3.1. Expert Questionnaire Design

The questionnaire survey contained two parts [14]. The first part aimed to confirm the evaluated factors in compound potential hazard analysis. Having integrated several literatures review, the preliminary factor structure for compound potential hazard analysis was drawn as **Table 4**. The second part tended to evaluate the relative importance among evaluated items so as to determine the hierarchic matrix in analytic hierarchy process (AHP) for final weights.

The questionnaire survey was divided into two stages for clarifying the relationship among the factors. Expert questionnaire survey, as the first stage, aimed to ensure the importance priority of factors in compound potential hazard analysis. 0 - 10 levels were utilized that the higher score was obtained, the more importance it would present. The results could become the reference for expert evaluations in the second stage. Total 10 expert questionnaires were collected. The experts were specialized in civil and hydraulic engineering, architecture, urban planning, and soil and water conservation. Seven of them appeared more than 10 years working experiences.

In the second stage, the experts compared the relative importance of the paired factors for the comparison matrices in various hierarchies, **Tables 5-8**. Meanwhile, the weights of the evaluated items in Hierarchy II in **Table 5** were multiplied by the weights of the factors in Hierarchy III in **Tables 6-8** for the weights of the final factors, **Table 9**. From **Table 9**, Slope in Environmental geology presented the highest weight, Flood potential appeared the highest weight in Natural disaster, and Land use zoning showed the highest weight in Land use. In this case, the hierarchic analysis of expert questionnaires could select the major items in Compound potential hazard analysis by weights.

3.2. Map Overlaying Criteria in GIS

Aiming at drawing the 40 m × 40 m grids around Changhua City in Taiwan, **Figure 1**, the criteria of Environmental geology, Natural disaster, and Land use acquired from expert questionnaires were proceeded map overlaying analyses in GIS for the values of grids. The weights acquired by AHP were applied to calculating the environmental risk in grids for compound potential hazard analysis. The descriptions of the criteria are showed as below.

As to Environmental geology criteria, environmental geology contained the items of Active faults, Active faults, Rock strength, Geological condition, and Slope. Each item has been classified as high, medium, and low risk of scores 3, 2, and 1, respectively. **Table 10** indicates the criteria descriptions.

Similarity, Natural disaster criteria includes Landslide potential score, Debris flow potential score, and Flood potential score. For landslide potential, the data analyses utilized the environmental geology database maps of the urban and the surrounding slopes in Central Geological Survey (CGS) in Taiwan, in which Landslide potential was based for divisions. Meanwhile, the debris flow potential streams and the influential areas announced by Soil and Water Conservation Bureau (SWCB), Taiwan was utilized for data analyses, in which debris flow potential was based for divisions. The landslide and debris

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Table 4. Hierarchic structure of evaluated items in compound potential hazard analysis.

Hierarchy I: Objective	Hierarchy II: Evaluated items	Hierarchy III: Factors
Compound potential hazard analysis	Environmental geology	Active faults
		Rock strength
		Geological condition
		Slope
	Natural disasters	Landslide potential
		Debris flow potential
		Flood potential
	Land use	Vegetation cover
		Human development
		Land use zoning

Table 5. Relative importance of evaluated items in Hierarchy II.

Hierarchic matrix	Environmental geology	Natural disaster	Land use	Weight
Environmental geology	1	0.1740	0.2387	9.08%
Natural disaster	5.7471	1	0.4673	36.45%
Land use	4.1894	2.1400	1	54.47%

Note: λ_{max} = 3.42; *C.I.* = 0.210; *C.R.* = 0.112.

Table 6. Relative importance of the factors in Environmental geology.

Hierarchic matrix	Active faults	Rock strength	Geological condition	Slope	Weight
Active faults	1	0.2075	0.2197	0.1839	5.80%
Rock strength	4.8204	1	0.2677	0.3281	15.85%
Geological condition	4.5509	3.7356	1	0.4884	33.06%
Slope	5.4371	3.0476	2.0477	1	45.29%

Note: λ_{max} = 4.26; *C.I.* = 0.086; *C.R.* = 0.095.

Table 7. Relative importance of the factors in Natural disaster.

Hierarchic matrix	Landslide potential	Debris flow potential	Flood potential	Weight
Landslide potential	1	0.5119	0.3769	17.48%
Debris flow potential	1.9537	1	0.5173	30.36%
Flood potential	2.6531	1.9332	1	52.17%

Note: λ_{max} = 3.01; *C.I.* = 0.007; *C.R.* = 0.012.

Table 8. Relative importance of factors in Land use.

Hierarchic matrix	Vegetation cover	Human development	Land use zoning	Weight
Vegetation cover	1	0.2889	0.3188	12.71%
Human development	3.4615	1	0.4	31.37%
Land use zoning	3.1366	2.5	1	55.92%

Note: λ_{max} = 3.12; *C.I.* = 0.058; *C.R.* = 0.100.

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Table 9. Weights of evaluated factors in Analytic Hierarchy Process (AHP).

Hierarchy I: Objective	Hierarchy II: Evaluated items	Hierarchy III: Factors	Weight
Compound potential hazard analysis	Environmental geology	Active faults	0.53%
		Rock condition	1.44%
		Geological condition	3.00%
	Natural disaster	Slope	4.11%
		Landslide potential	6.37%
		Debris flow potential	11.06%
		Flood potential	19.01%
	Land use	Vegetation cover	6.92%
		Human development	17.09%
		Land use zoning	30.46%

Table 10. The descriptions of the criteria score.

Evaluated items	Factors	Score	Description
Environmental geology	Active faults	High risk (3)	The base locates within 100 m from confirmed fault area
		Medium risk (2)	The base locates within 100 m - 1000 m from confirmed fault area
		Low risk (1)	The base locates more than 1000m away from confirmed fault area
	Rock strength	High risk (3)	Rock strength below 100 kg/cm^2
		Medium risk (2)	Rock strength within 100 – 250 kg/cm^2
		Low risk (1)	Rock strength above 250 kg/cm^2
	Geological condition	High risk (3)	Ill geological condition results in high disaster risk
		Medium risk (2)	Ordinary geological condition results in low disaster risk
		Low risk (1)	Good geological condition
Natural disaster	Slope	High risk (3)	Slope above 30%
		Medium risk (2)	Slope within 5% - 30%
		Low risk (1)	Slope below 5%
	Landslide potential	High risk (3)	According to the database of Central Geological Survey, Taiwan
		Medium risk (2)	
		Low risk (1)	
	Debris flow potential	High risk (3)	According to the database of Soil and Water Conservation Bureau, Taiwan
		Medium risk (2)	
		Low risk (1)	
	Flood potential	High risk (3)	Flooding depth above 2 m
		Medium risk (2)	Flooding depth within 0.5 m - 2 m
		Low risk (1)	Flooding depth below 0.5 m
Land use	Vegetation cover	High risk (3)	Vegetation cover below 50%
		Medium risk (2)	Vegetation cover within 50% - 80%
		Low risk (1)	Vegetation cover above 80%
	Human development	High risk (3)	Human development above 60%
		Medium risk (2)	Human development within 40% - 60%
		Low risk (1)	Human development below 40%
	Land use	High risk (3)	Non-forest or agricultural area above 70%
		Medium risk (2)	Non-forest or agricultural area within 30% - 70%
		Low risk (1)	Non-forest or agricultural area below 30%

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flow potential risk intensities were defined by CGS and SWCB, as to abide by the definitions of this research. The flooding areas were also utilized when the accumulated rainfall achieving 600 mm, announced by Water Resources Agency, Taiwan for data analyses, in which the flooding depth was applied to analyses in **Table 10**.

This study utilized the results of national land survey by National Land Surveying and Mapping Center, Taiwan in 2007 for analyzing the criteria of the Land use. Based on the types of land use to determine the relevant indices, the area corresponding to the items in the 40m grid was calculated. According to the percentage of the grid in the total area, three levels were divided for risk evaluation. Vegetation cover score, Human development score, and Land use score were obtained by analyzing the ratio of Vegetation cover area, Human development area, and Non-forest or agricultural areas in the 40 m grids, respectively, shown as in **Table 10**.

3.3. Outcomes of Map Overlaying Analyses in GIS

Having Changhua City as the studied area, the north end of Baguashan is located on the south, Wu River is next to the east and the north, the west and the north areas are plain terrain, and the elevation is within 0 m - 231.5 m (see **Figure 1**).

In the first step, consider the Environmental geology criteria. The result of Active faults score in the studied area covered Changhua fault through the plain in the west, was shown as **Figure 2**. As Rock strength score, Rock strength in the studied area was less than 100 kg/cm^2 that it was regarded as High risk area (**Figure 3**). Geological condition score in the studied area was considered ill Geological condition and it was regarded as the high disaster risk area, in **Figure 4**. The last score, Slope score, based on 5 m × 5 m digital elevation model (DEM) to precede slope analyses, **Figure 5**, the average slope was 11.53%, and most areas appeared 5%.

The second step for Natural disaster criteria, there was no debris flow potential stream in the studied area, so the Debris flow potential risk was not considered. The landslide potential area in **Figure 4** represented the score value 3 and the non-landslide area 1 for calculations. In Flood potential consideration, the flooding areas when the accumulated rainfall being 600 mm, announced by Water Resources Agency in Taiwan, were utilized for data analyses. The flooding depth was the analysis criteria, shown in **Figure 6**. In the third step, Land use criteria, based on the results of the national land survey from National Land Surveying and Mapping Center, Taiwan in 2007, **Figure 7**, the risk level (**Figures 8-10**) according to **Figure 7** and **Table 10** for Land use was evaluated.

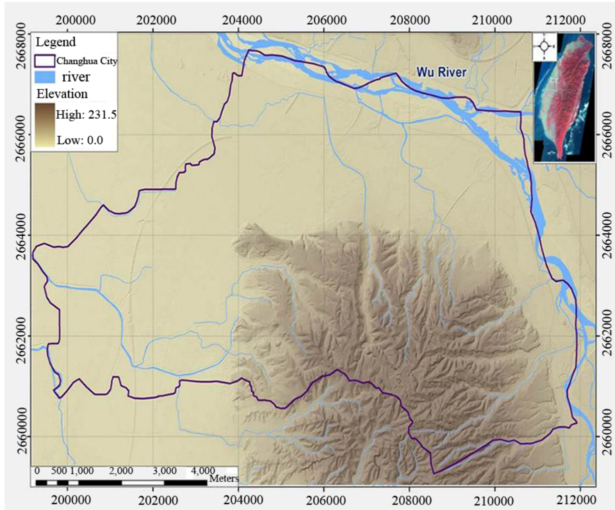

Figure 1. Topography of the studied area.

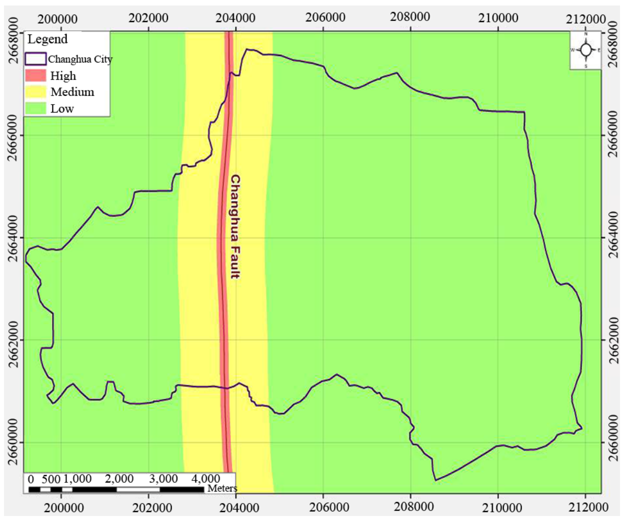

Figure 2. Active fault distribution in the studied area.

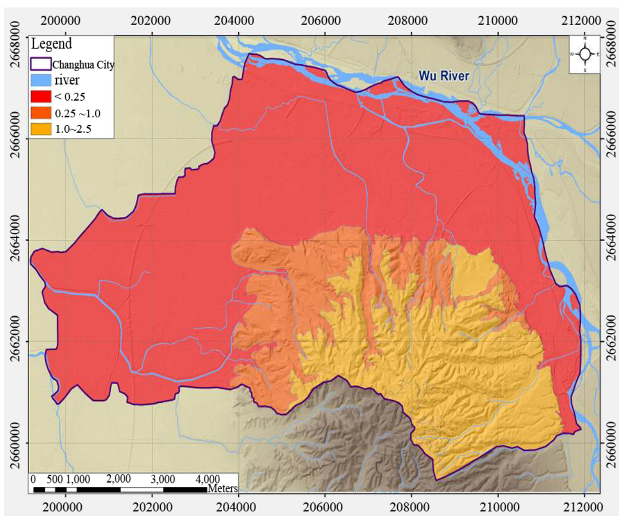

Figure 3. Rock strength distribution in the studied area.

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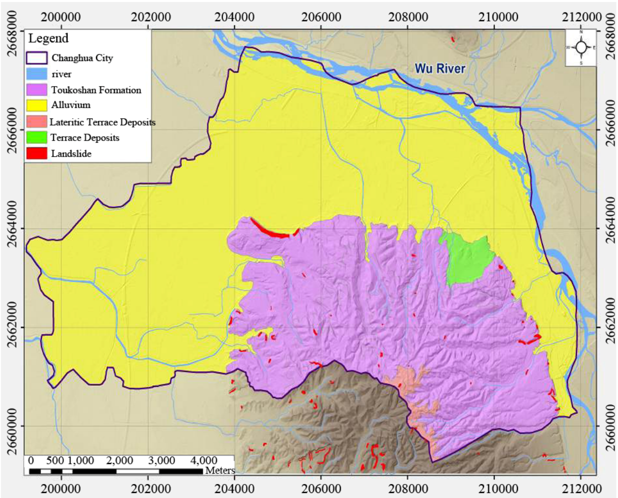

Figure 4. Geological condition and landslide potential distribution in the studied area.

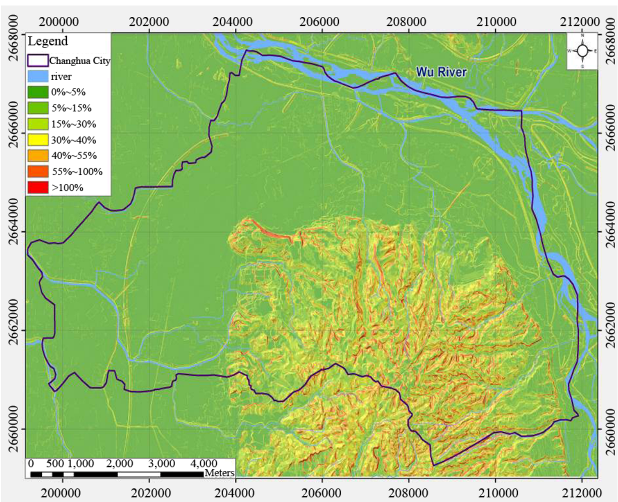

Figure 5. Slope distribution in the studied area.

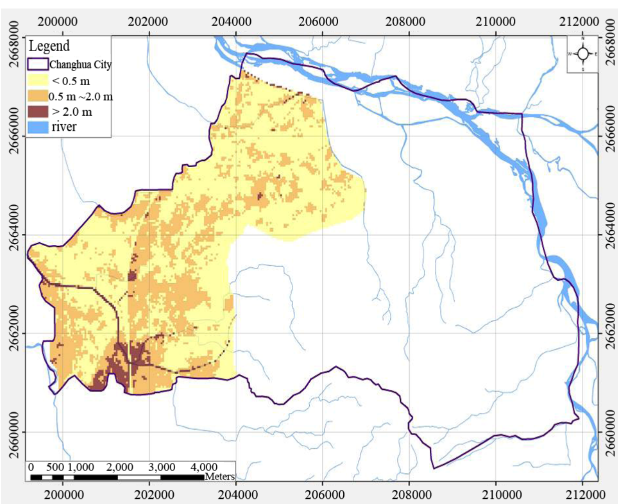

Figure 6. Flood potential distribution in the studied area with accumulated rainfall 600 mm.

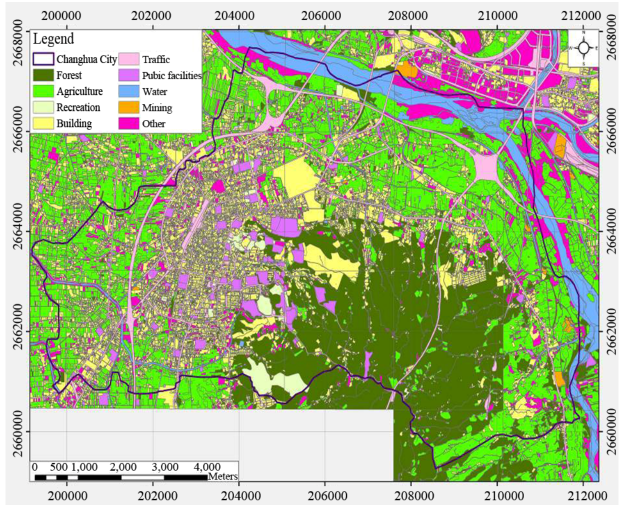

Figure 7. Land use distribution in the studied area.

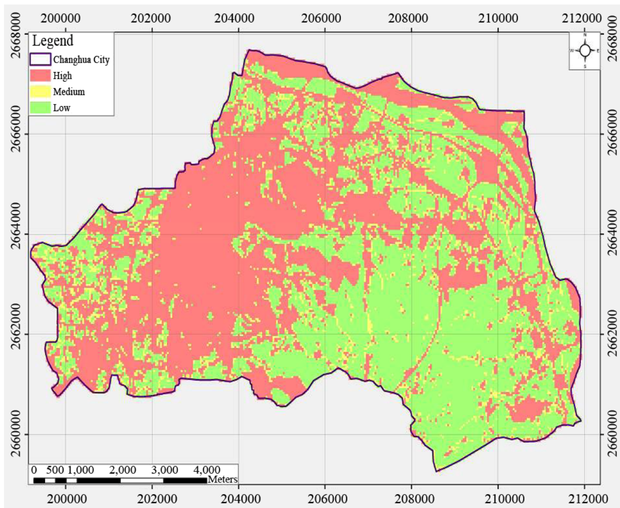

Figure 8. Vegetation cover distribution in the studied area.

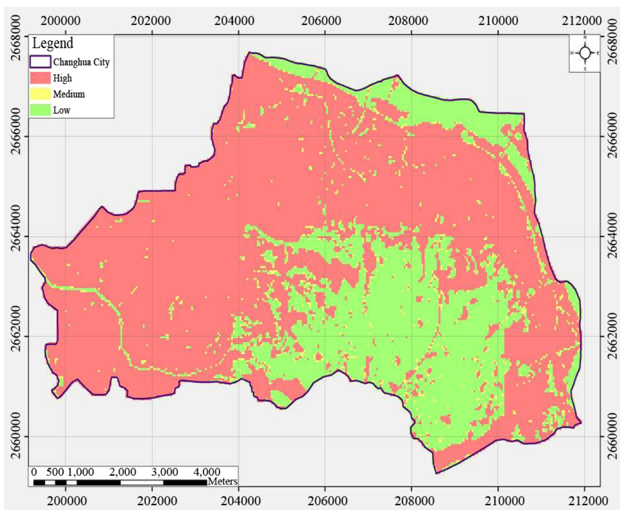

Figure 9. Human development distribution in the studied area.

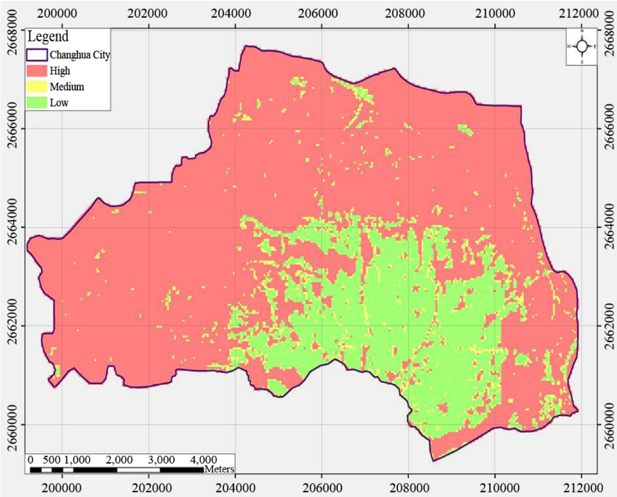

Figure 10. Land use distribution in the studied area.

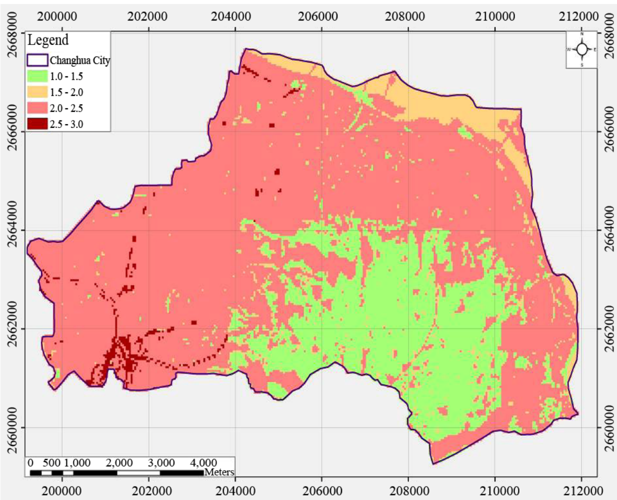

Figure 11. Environmental risk distribution in the studied area.

Finally, by summing up the weights in AHP, the Environmental Risk in the grids was calculated, **Figure 11**. Based on **Tables 9** and **10**, we obtained the Environmental Risk by the product of factors (**Figures 2-10**) and weightings (**Table 9**). Having considered the factors of Environmental geology, Natural disaster, and Land use, the results acquired from AHP and map overlaying in GIS presented that the higher score value was shown, the higher disaster potential would present, **Figure 11**. The reference of the results could be provided to those who have the relevant planning of researches.

4. Conclusion

With expert survey to formulate the weight analysis, various types of disasters were overlaid to form the compound potential hazard map. Traditional numerical simulation merely simulated single disaster [15,16]. However, this study combines the present map information (including traditional numerical simulation results), expert questionnaires, and overlaying analyses in Geographic Information Systems, aiming to clarify the relationship among factors in compound potential hazard analysis. Based on the weights of factors from expert questionnaire analyses, more important evaluated items were selected. Such results could provide reference for the personnel related to disaster prevention. Moreover, the future security evaluation for hideout points and evacuation routes and the development of geographic information systems could also base on the results.

5. Acknowledgements

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