

Spatial Analytic Hierarchy Process Model for Flood Forecasting: An Integrated Approach

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Abstract. Various flood influencing factors such as rainfall, geology, slope gradient, land use, soil type, drainage density, temperature etc. are generally considered for flood hazard assessment. However, lack of appropriate handling/integration of data from different sources is a challenge that can make any spatial forecasting difficult and inaccurate. Availability of accurate flood maps and thorough understanding of the subsurface conditions can adequately enhance flood disasters management. This study presents an approach that attempts to provide a solution to this drawback by combining Geographic Information System (GIS)-based Analytic Hierarchy Process (AHP) model as spatial forecasting tools. In achieving the set objectives, spatial forecasting of flood susceptible zones in the study area was made. A total number of five set of criteria/factors believed to be influencing flood generation in the study area were selected. Priority weights were assigned to each criterion/factor based on Saaty's nine point scale of preference and weights were further normalized through the AHP. The model was integrated into a GIS system in order to produce a flood forecasting map.

1. Introduction

In reality, flood control decision making tries to lessen the flood damages; to reduce the depth of floodwater in floodplain zones; and also to reduce the flooding period to support victims. These issues are usually too sophisticated and ill-structured to be considered from the study of just one criterion, characteristic, or perspective hoping that it will result in the most desirable decision [1]. In fact, this kind of single dimensional strategy is only over-simplification of the real flood challenges at hand, which can result in unrealistic decisions. A much more desirable approach is the simultaneous consideration of all suitable criteria which are associated with the specific floodplain management problems. This important issue should be putting into cognizance in the development of decision making models. Dealing with such issues comprises the key point of interest in Multi-Criteria Decision Analysis (MCDA).

MCDA comprises of a complex aspect of operational research, which is specialized in the development and execution of decision support tools and methods to address sophisticated decision challenges involving numerous criteria, goals, or objectives of contradicting flood challenges. The various tools and methods available from MCDA are not just some mathematical models aggregating criteria, opinions, or attributes, but in addition are decision support oriented. Support serves as a major concept in MCDA, meaning that the models are certainly not designed by way of a straightforward sequential way in which the decision maker's role is passive. Rather, a repetitive method is used to analyse the priorities of the decision maker and represent them as regularly as it can be in a suitable decision model. This repetitive and interactive preference modelling process comprises the main foundation of the decision support orientation of MCDA. It is among the fundamental unique features of the MCDA in contrast to traditional stochastic and optimization decision making strategies [2]. In this study, the principles of the Multi-Criteria Decision Making (MCDM) in the context of Analytic Hierarchy Process (AHP) have been integrated into GIS to simulate and forecast the flood susceptible zones. AHP is a mathematical modeling technique for multi-criteria decision making ([3-5]. It was



developed by Saaty, a mathematician in the early 70s. The AHP method helps to specify numerical weights representing the relative importance of factors, elements, criteria for flood susceptibility models [5-8]. AHP allows both qualitative and quantitative approaches to solve complex decision problems. The technique structures/decomposes problems into a hierarchy of elements or factors influencing a system by incorporating levels. In quantitative aspects, the AHP can prioritize a set of attributes and distinguish in general the more important factors from the less important factors. The pair-wise comparison judgments were made with respect to the attributes of one level of hierarchy given the attribute of the next higher level of hierarchy (from the main criteria to the sub-criteria).

The majority of the work and literature available on the application of AHP in geo-engineering is dedicated to the generation of relative weights of influential factors and integration of the weights into a GIS environment. AHP's comprehensive literature collections can be found at <http://www.expertchoice.com>. For instance, Dai et al[9] generated relative weights of influential factors affecting urban (Lanzhou city, China) geo-environment using AHP, where the suitability potentials of urban land use were evaluated using GIS. Recently, Dano et al[10] used AHP in finding the most suitable sites to propose a new recreational park for Universiti Teknologi Malaysia. Similarly Ayalew et al[11] employed pairwise comparisons to come up with the relative weights of landslide controlling factors, where he further used GIS to develop a landslide risk assessment map for Tsugawa area of Agano River, Niigata Prefecture, Japan. Moreover, Komac[12] adopted the multivariate statistical analysis where he came to the conclusion that the use of the AHP method provides a way of defining the factor's weights in the linear landslide susceptibility model. Its vast application is based on its simplicity, ease of use, and profound flexibility inherent in the approach [13]. The objectives are to develop a flood susceptibility map based on the views of two category of experts (hydrologists and geologists) using some hydrogeological indexes. The data preparation and integration were carried out in a GIS environment.

2. Study area

The State of Perlis is bounded by Thailand in the north, and Kedah in the south, while its western coastline borders the Straits of Malacca as illustrated in Fig. 1. It is bounded by longitudes $100^{\circ} 07' 02''\text{E}$ / $100^{\circ} 22' 33''\text{E}$ and latitudes $6^{\circ} 43' 19''\text{N}$ / $6^{\circ} 15' 13''\text{N}$ respectively. Perlis is chosen due to her prone to flooding as what had happened in 2010.

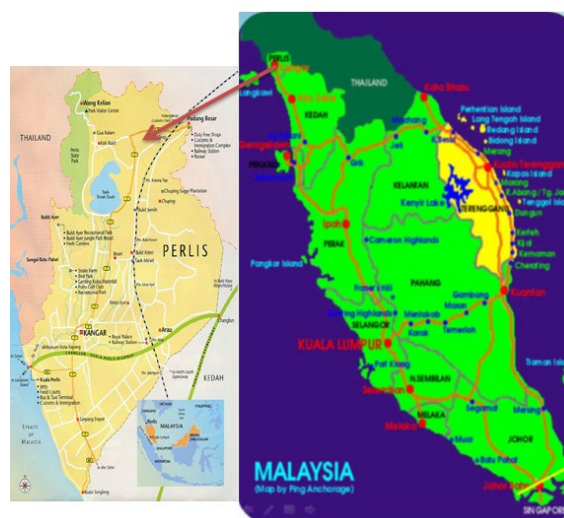


Figure 1: Map of Peninsular Malaysia showing the study area Perlis.

3. Methodology

3.1. Weighting the flood-Influencing criteria/factors

Based on the method of the MCDM, each factor's weight was computed and assigned to the factors discussed previously in GIS environment. [14-16] described MCDM as a method that permits each criterion to be weighted with respect to its relative importance/influence. Experts' judgments were used in assigning the weight of each criterion. The experts' ratings were aggregated using a Geometric Mean method as follows: Geometric Means = $((X_1)(X_2)(X_3)....(X_N))^{1/N}$; where X = Individual score and N = Sample size (Number of scores). Therefore, the experts' preferences helped in carrying out the pairwise comparison matrix. As mentioned earlier, AHP technique developed by [17] was used in producing the relative weights based on the Saaty's scale of influence 1 to 9 as shown in Table 1. The weights of the factors were generated based on the steps described by [18].

3.2 AHP integration into GIS system

In this stage, the AHP results were integrated into a GIS system to simulate the flood vulnerable areas. The combination of all the thematic layers (the factors) using the Weighted Linear Combination (WLC) method in accordance to the computed weights was carried out in a GIS. The Weighted Linear Combination, or simple additive weighting, relies on the concept of a weighted average where continuous criteria are standardized to a collective numeric range, and then combined by means of a weighted average [19]. The overlay of the thematic layers was to obtain the final simulation of the flood forecasted zones. The results of the final analysis managed to indicate the potential flood areas in the study area.

4. Results & Discussion

4.1 Pairwise comparisons of the factors

It is normally presumed that MCDA started at the beginning of 60s. A good number of experts of MCDA considered that their discipline stems mainly from the early work on goal programming as well as study of Drobne and Lisec [19] and Simon [20]. Simon[20] proposes a framework for analysing human decision-making processes by differentiating between the intelligence, design, along with choice phases MCDA techniques are numerical algorithms that define suitability of a particular solution on the basis of the input criteria and weight together with some mathematical or logical means of determining trade-offs when conflict arise. By this technique, a weight value ranges from 1 to 9 was assigned to each factor by the experts to reflect their relative significance. Using the WLC method, all the map layers (the factors) were overlaid in the final GIS spatial analysis for flood susceptible zones simulation.

The WLC technique can be carried out using any type of GIS system possessing the overlay. This permits the evaluation criterion map layers to be overlaid in order to obtain the composite map layer which is output. Therefore, the output of this WLC method gave a map which simulated the most potential flood susceptible zones of Perlis. Figure 2 shows the flood forecasting model. The responses of the experts were computed in Table 1 and 2 below: Where, RF = Rainfall; GL = Geology; ST = Soil type; S = Slope; LU = Land use.

Table 1: A matrix of pair-wise comparisons of five criteria for the AHP process.

| | RF | GL | ST | S | LU |
|-----|------|-------|-------|------|------|
| RF | 1.00 | 4.92 | 3.41 | 2.30 | 3.61 |
| GL | 0.20 | 1.00 | 2.05 | 0.39 | 0.48 |
| ST | 0.29 | 0.49 | 1.00 | 0.70 | 0.46 |
| S | 0.44 | 2.58 | 1.42 | 1.00 | 0.60 |
| LU | 0.28 | 2.08 | 2.17 | 1.66 | 1.00 |
| SUM | 2.21 | 11.07 | 10.05 | 6.05 | 6.15 |

Table 2: Determined relative criterion weights.

| | RF | GL | ST | S | LU | Weights |
|-----|------|------|------|------|------|---------|
| RF | 0.45 | 0.44 | 0.34 | 0.38 | 0.59 | 0.44 |
| GL | 0.09 | 0.09 | 0.20 | 0.06 | 0.08 | 0.11 |
| ST | 0.13 | 0.04 | 0.10 | 0.12 | 0.07 | 0.09 |
| S | 0.20 | 0.23 | 0.14 | 0.17 | 0.10 | 0.17 |
| LU | 0.13 | 0.19 | 0.22 | 0.27 | 0.16 | 0.19 |
| SUM | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |

Table 3: Determined Consistency Ratio (CR).

| STEP I : | | | | | | | | | | | |
|----------|------|------|------|------|------|------------------------|---|------|------|--|-------|
| RF | 1.00 | 4.92 | 3.41 | 2.30 | 3.61 | | | | | | |
| GL | 0.20 | 1.00 | 2.05 | 0.39 | 0.48 | | | | | | |
| ST | 0.29 | 0.49 | 1.00 | 0.70 | 0.46 | | | | | | |
| S | 0.44 | 2.58 | 1.42 | 1.00 | 0.60 | | | | | | |
| LU | 0.28 | 2.08 | 2.17 | 1.66 | 1.00 | | | | | | |
| | | * | | | | STEP II : SUM1/WEIGHTH | | | | | |
| | 0.44 | 0.11 | 0.09 | 0.17 | 0.19 | | | | | | |
| | | = | | | | SUM1 | | | | | |
| RF | 0.44 | 0.52 | 0.32 | 0.38 | 0.70 | 2.36 | | 0.44 | | | 5.36 |
| GL | 0.09 | 0.11 | 0.19 | 0.07 | 0.09 | 0.54 | / | 0.11 | = | | 5.14 |
| ST | 0.13 | 0.05 | 0.09 | 0.12 | 0.09 | 0.48 | | 0.09 | | | 5.14 |
| S | 0.19 | 0.27 | 0.13 | 0.17 | 0.12 | 0.88 | | 0.17 | | | 5.27 |
| LU | 0.12 | 0.22 | 0.20 | 0.28 | 0.19 | 1.02 | | 0.19 | | | 5.25 |
| | | | | | | | | | SUM2 | | 26.16 |

Table 4: Random Inconsistency Indices.

| n | 3.00 | 4.00 | 5.00 | 6.00 | 7.00 | 8.00 | 9.00 | 10.00 |
|----|------|------|------|------|------|------|------|-------|
| RI | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 |

The Consistency Index (CI), which is a measure of departure from consistency, was calculated using the formula:

$$CI = \frac{\lambda - n}{n - 1} \quad (1)$$

Where, n = number of factors (i.e. 5) and λ = average value of the consistency vector determined in step ii above.

$$\lambda = 5.36 + 5.14 + 5.14 + 5.27 + 5.25 = 26.16/5 = 5.23$$

Based on equation (3), $CI = 5.23 - 5/5 - 1 = 0.06$

In order to assess the robustness of the expert view the Consistency Ratio (CR) was calculated using equation (2). The result is shown in Table 3.

$$CR = \frac{CI}{RI} \quad (2)$$

Where, RI is the random inconsistency index whose value depends on the number (n) of factors being compared; for n = 5, RI = 1.12 as illustrated in Table 4 [17].

Using Equation (4),

$$CR = \frac{0.06}{1.12} = 0.05$$

Therefore, since $0.05 < 0.1$, it indicates that there is a realistic degree of consistency in the pairwise comparison and as a result, the weights 0.44, 0.11, 0.09, 0.17 and 0.19 can be assigned to rainfall, geology, soil type, slope and land use respectively.

4.2 AHP spatial flood forecasting model

The combination of all parameters was carried out in GIS using the WLC method. This is based on the weights generated from the AHP. The Weighted Linear Combination (WLC) formula is shown below:

$$FSZ = \sum w_i x_i \quad (3)$$

Where, *FSZ* is the Flood Susceptible Zones; w_i is the factors weights which must sum up to 1, and x_i is the criterion score *i*. All these relevant data were uploaded into the GIS system before analysis was carried out using a total of five thematic maps: land use, geology, rainfall distribution, soil type and slope gradient. Figure 2 presents the result of the GIS spatial simulation model for flood susceptible zones. In Figure 2, the light blue, yellow, red, white and pink colors represent very highly, high, moderate, little as well as hardly susceptible zones to flooding. These are basically based on the ratings of the flood influencing factors given by the experts.

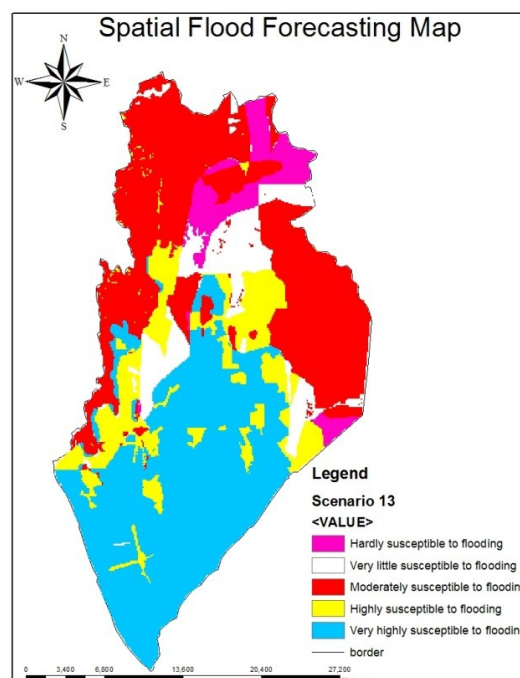


Figure 2: Map of forecasted flood susceptible zones of Perlis.

5. Conclusion

In this study, a GIS-based Analytic Hierarchy Process was successfully applied in simulating the flood susceptible zones for Perlis State. In recent years, GIS proved profound potentials in combating flood catastrophes. The social and economic losses as a result of flood disasters, technologic crises, as well as global epidemics are growing; needing more effective group decision making under uncertainty. In this study, the efficiency of GIS-based AHP as spatial multi-criteria forecasting tool was discovered. Hence, this system will help civil authorities such as planners and emergency agency in taking positive and in-time steps during the pre-disaster situations. It will similarly help them during post-disaster activities to assess damages and losses caused as a result of flood.

6. References

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