Application of the Fuzzy Method to Improve GIS Geomorphological Method of Predicting Flood Vulnerable Area

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Abstract: In identifying flood vulnerable areas, three methods are generally deployed: the geomorphology method which is based on topographic features; the past evidence method based on observed data of past actual floods; and, prediction of flood areas through hydrologic models.
This study aims to improve the prediction model of the geomorphology method through the application of fuzzy method in GIS modeling. The generally used GIS method of superimposing thematic map layers assumes crisp boundaries of the layers, which results in either risk-averse solutions or risk-taking solutions. The introduction of fuzzy concepts to processing of evaluation criteria (DEM, slope, aspect) solves this problem.
As the result of applying the fuzzy method to a test site in the west Nak-Dong river, similar flood vulnerable areas were predicted as when using the conventional Boolean criteria. The resulting map, however, showed varying degree of uncertainty of flooding in these areas. This extra information is deemed to be valuable in taking phased actions during flood response, leading to a more effective and timely decision-making.

Keywords: DEM, fuzzy, flood vulnerable area.

1. Introduction

Every year Korea is hit by a series of typhoon attacks and the amplified effect of typhoon and abnormal weather changes cause flood and inundations inflicting large-scale physical damage as well as loss of human lives. Despite much effort to establish effective measures of planning, preparation, response and rehabilitation in dealing with such disaster, progress seems to be slow.

One recent action taken by the government was the production of flood risk maps and flood inundation scenario maps to accurately forecast vulnerable areas enabling timely decisions to prevent and minimize damage in case of a typhoon or heavy rain storm. Also maps are created of past flood inundation regions[1]. These past flood-trace-maps are compiled based on past data and records of past 30 years[6]. Despite thorough study and collection of related data, omission of flooded regions which have not been reported or recorded is inevitable. These flood-trace-maps although useful in many situations, cannot serve as a comprehensive basic data in assessing flood risks at a national or state level. Other methods of predicting flood vulnerable areas include the geomorphology method and the hydrologic modeling method[2].

In this study the geomorphology method was selected to predict the flood vulnerable areas. Past flood-trace-maps were referenced to determine the geomorphologic threshold values. The fuzzy method was applied to improve the flood risk map. The method was experimented with a dataset covering west Nak-Dong river watershed. This area has been flooded on July of 1989 due to heavy rainfall brought by the typhoon Judy.

2. The geomorphology method and the fuzzy method

The geomorphology method uses landscape features such as natural dikes and waterways to predict flood vulnerable areas. Geomorphologic features are the result of natural evolution of earth surface going through repetitive natural process of erosion, sedimentation and weathering. By studying flooded area it is possible to identify common geomorphologic features and then predict future flood areas by extrapolating the common geomorphologic features of the flooded area to other areas of interest[9].

Past evidence method uses flood trace maps to identify the extend of flood vulnerable areas for future floods. This method relies on actual flood records from where data such as inundation area and inundation depth are gathered. This method is the most reliable method but it has the flaw of being useful only with a large amount of accumulated past records.

The hydrological method uses hydrologic models with parameters such as inundation area, inundation depth, length of period to predict flood vulnerable areas. The disadvantage of this method is that large amount of accurate data is required and is the most expensive and time consuming method of the three methods [1][5].

In this study, the geomorphology method was used to predict vulnerable flood area to present a solution in case of insufficient flood records. Fuzzification in GIS, is a normalization process of the evaluation criteria based on set membership[3]. Using the membership function of the fuzzy theory, the Boolean concept of "Yes" or "No" is extended to embrace non-deterministic situations and to deal with concepts such as "more likely" or "less likely". The membership function can be interpreted as a measure of membership and the fuzzy numbers are distributed between 0 and 1 or between 0 and 255 to visualize as grey values. Different types of membership functions exist, i.e., S-, J- and linear[4]. The fuzzy evaluation criteria then need to be ranked or weighted. The AHP(Analytic Hierarchy Process) is commonly used to assign different weights to various criteria[10].

It is usual in GIS overlay analysis to superimpose two layers to produce a resulting layer with crisp boundaries. This crisp boundaries however, is an unrealistic representation of the real phenomena. The Boolean representation of 'either or' is improved by the adoption of the fuzzy representation where an area is not represented as "flood vulnerable" and "non-flood vulnerable" but rather in varying degrees of uncertainty represented by the membership function. The varying degree of uncertainty is a more realistic representation of the actual phenomena and thus result in a better decision in preparation or response to flood disaster situation. The application of fuzzy method to decision making process is followed as shown in Fig. 1.

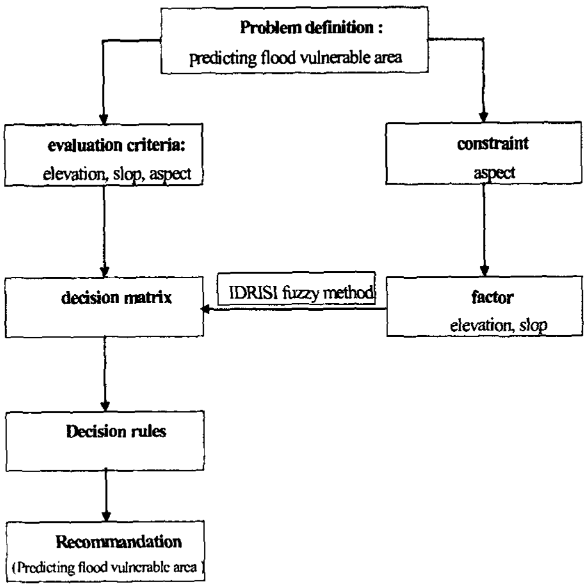

Fig. 1. Application of fuzzy method to decision making.

3. Mapping the flood vulnerable area

To apply the fuzzy method in mapping the flood vulnerable area, various existing data sets had to be gathered, prepared and analysed. Collecting the correct data sets to be applied to a GIS data model is the most time consuming and expensive task of the whole decision making process.

The collected data sets for this experiment were past flood trace map of 1989, digital map of scale 1/5,000, digital orthoimage, and a reports of study on past floods. The geographic boundary was limited to west Nak-Dong river including parts of Kimhae city (Fig. 2).

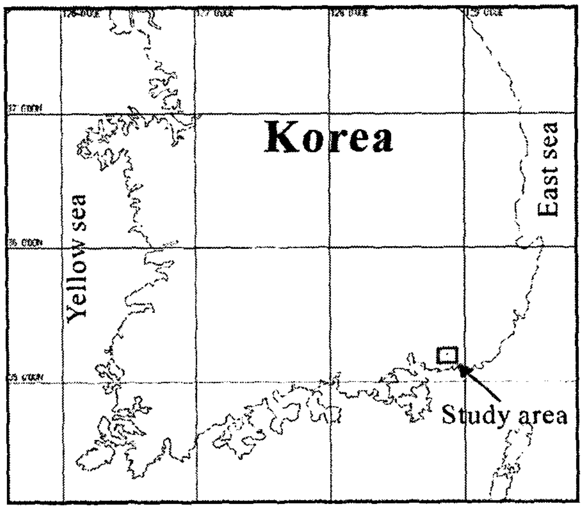

Fig. 2. Map of test site.

For the preparation of various data layers for spatial analysis, ArcGIS, the commercial product from ESRI company was used and IDRISI software from Clarke University was also used for creation of the maps.

DEM(Digital Elevation Model) was initially produced and slope and aspect maps were subsequently produced. The landuse of this area was identified from digital orthophoto (Fig.3) as agricultural with most of the area being covered with rice fields.

Fig. 3. Digital orthophoto of west Nak-Dong area.

1) Geomorphological Analaysis

DEM and past flood trace map were analysed to get topographic characteristics of the test site. The highest point was 630m high and 99% of the flooded area was below 10m. The 10m level was chosen as important evaluation criteria in subsequent modeling. An overlay of the flood trace map and DEM is as shown in Fig. 4.

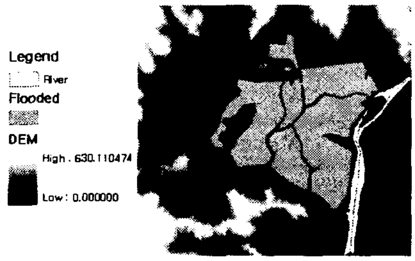

Fig. 4. Elevation map overlayed with flood trace map.

DEM was also used to compute the slopes and a slope map was created and overlayed with the past flood trace map (Fig. 5). The steepest slope of the test site was 63 degrees and 99% of the flooded area had slopes of less than 4 degrees. This criteria was also used in subsequent modeling.

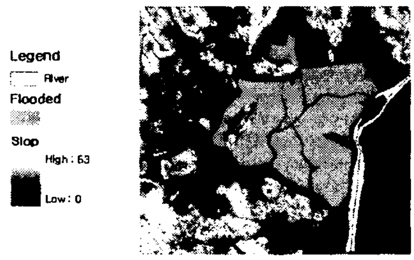

Fig. 5. Slope map overlayed with flood trace map.

Aspect values were classified into 9 different values after computation of the aspect value of each grid cell. The 9th direction was given a -1 value to represent a planar grid cell. 93% of the flood area in the flood trace map had planar grid cells (Fig. 6).

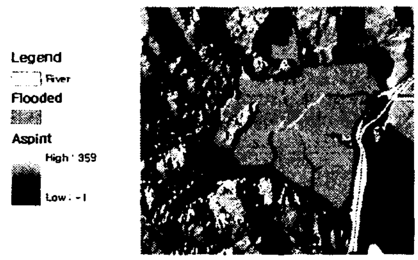

Fig. 6. Aspect map overlayed with flood trace map.

The 3 evaluation criteria were then overlayed with the <AND> condition to get a flood prediction map using the geomorphology method (Fig.7).

Fig. 7. Flood prediction map.

The green area represents non-flooding area and the blue area show the flood vulnerable area.

A comparison with past flood trace map showed a little difference along the north western part and large area in the south eastern part (Fig. 8). Interpretation from digital orthophoto showed that the main reason for this difference was due to drainage capacity at the north western part and the existence of a man made levee along the south eastern area.

Fig. 8. Flood prediction map overlayed with flood trace map.

2) The fuzzification process

In the fuzzification process the evaluation criteria areclassification into constraints and factors[7]. Constraints acts to diminish the effect of the criteria in consideration and works similarly to the Boolean map where results are represented as 0 or 1. Factors on the other hand, are represented on a continuous scale where evaluation criteria gets a higher value depending on its suitability to the objective.

In this study, the aspect criteria was processed as a constraint because 93% of the flooded area was a–1 planar grid cell value. Elevation and slope criteria were processed with sigmoid membership function with values ranging from 0 to 255. The sigmoid membership function is generally used in the fuzzification process [8][11]. Fig. 9 shows the result of applying the fuzzy logic to the evaluation criteria and Fig.10 shows the fuzzified map overlayed with DEM and the flood trace map.

Fig. 9. Fuzzified flood prediction map.

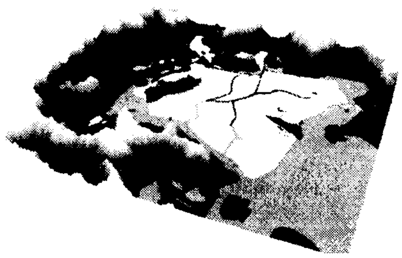

Fig. 10. Fuzzified flood prediction map overlayed with DEM and flood trace map.

As can be seen from Fig. 9, the fuzzified flood prediction map is similar to the conventional Boolean overlay flood prediction map. However, the identified flood vulnerable regions are classified on a continuous scale of 0 to 255. This represents the uncertainty level of flood in this areas and this information can be used for phased decision making for prevention planning, preparation and response.

4. Conclusions

In this study the geomorphology method of predicting flood vulnerable areas was deployed to create the flood prediction map. Various data sets of Nak-Dong river such as digital map, digital orthoimage, past flood trace maps were used to produce evaluation criteria maps. The evaluation criteria of elevation, slope and aspect were used in the conventional GIS Boolean overlay function to produce a flood prediction map. Then fuzzification process for the evaluation criteria was carried out to produce another flood prediction map. These two results were compared. Some conclusions of this study are introduced as follows.

1. The geomorphology method of predicting flood vulnerable areas using the conventional GIS Boolean overlay produced a closely matching map with the past flood trace map. The <AND> condition was applied for the elevation, slope and aspect evaluation criteria.
2. Fuzzified flood prediction map was produced with plane constraint and elevation and slope factors. Elevation and slope criteria were processed with sigmoid membership function with values ranging from 0 to 255. The fuzzified map matched closely the Boolean overlay map.
3. The fuzzified map represents flood vulnerability in varying degrees which is thought to be an improvement from the Boolean flood prediction map. The uncertainty information can be used for timely decision making in times of actual flood as well as for planning phase and the response phase.

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