ANALYSING FLOOD VULNERABLE AREAS WITH MULTICRITERIA EVALUATION

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ABSTRACT:

Cell-based Multicriteria Evaluation (MCE) methods are used to analyse the flood vulnerable areas. Flood disaster has a very special place in natural hazards. Its effect area is not bounded; it is an unusual event of a river basin. The aim in integrating Multicriteria Decision Analysis (MCDA) with Geographical Information Systems (GIS) is to provide more flexible and more accurate decisions to the decision makers in order to evaluate the effective factors. Some of the causative factors for flooding in watershed are taken into account as annual rainfall, size of watershed, basin slope, gradient of main drainage channel, drainage density, land use and the type of soil. In this study two main MCE approaches employed in GIS are used, namely Boolean and Weighted Linear Combination (WLC), and the issues and problems associated with both are discussed. In MCE, two methods, namely Ranking Method and Pairwise Comparison Method, are used to calculate the weights of each factor. Pairwise Comparison Method is integrated in GIS. An interface for pairwise comparison is created in Visual Basic Application embedded in ArcView 8.1 which is a GIS software program. The different results obtained from these two methods indicate the importance of the decision maker in determining the weights and the proper method, and making the decision. Furthermore, the concept of uncertainty in standardized criteria with MCE is evaluated. The standardized values of the factors are considered as a fuzzy measure concept expressed as fuzzy set membership. Some regular weights that are determined using Ordered Weighted Averaging are combined with the standardized values using WLC to recast the vulnerable areas. Thus the distribution of the weights of the criteria and compensating for each criterion by another one are seen in the solution set. A case study of flood vulnerable areas determination in Bartın Basin in the West of Black Sea Region is employed to illustrate the different approaches. To store the existing flood vulnerable areas in decision support system of General Directorate of Land Registry and Cadastre will provide some advantages to able to get answer for the questions of “How much area is vulnerable to flood?, What amount of the total area belongs to the government, or the real or judicial person?, Is there any area to be able to exchange by the treasury goods? How much?, what are the needs and cost to move through the non-vulnerable areas?”.

1. INTRODUCTION

Many nations experience fatalities and injuries, property damage, and economic and social disruption resulting from natural disasters. Natural disasters, such as earthquakes, hurricanes, flash floods, volcanic eruptions, and landslides have always constituted a major problem in many developing and developed countries. The natural hazards kill thousands of people and destroy billions of dollars worth habitat and property each year. The rapid growth of the world’s population has escalated both the frequency and severity of the natural disasters. Flood disaster has a very special place in natural hazards. Floods are the costliest natural hazard in the world and account for 31 per cent of economic losses resulting from natural catastrophes. Especially, river flooding has been a major natural hazard worldwide in recent events, e.g., Easter in the UK in 1998, Eastern Europe in 1998 and 1999, China in 1998, and Venezuela in 1999 (Sanders and Tabuchi, 2000). 1998 the South of China Floods Series took more than four months, 20 million people were affected in socio-economic life, thousands of people died and it caused the physical loss of approximately 20 billion USA Dollars (Türkiye Müteahhitler Birliği, 1998).

Flood related problems and many other applications proved that these problems could be solved through planning studies and detailed projects about flood prone areas. Determining the flood vulnerable areas is important for decision makers for planning and management activities.

Decision making is a choice or selection of alternative course of action in many fields, both the social and natural sciences. The unavoidable problems in these fields necessitate detailed analysis considering a large number of different criteria. All these criteria need to be evaluated for decision analysis. In a classification based on Boolean Logic, an area is either accepted or rejected based on a given threshold value. Besides the problems associated with the use of Boolean Logic, multi-criteria evaluation (MCE) methods have been applied. Since 80 per cent of data used by decision makers is related geographically (Malczewski, 1999a), Geographical Information System (GIS) may provide more and better information about decision making situations. GIS allows the decision maker to identify a list meeting a predefined set of criteria with the overlay process (Heywood et al., 1993) and the multicriteria decision analysis within GIS may be used to develop and evaluate alternative plans that may facilitate compromise among interested parties (Malczewski, 1996).

Lin et al. (1997) presented a GIS-based multicriteria evaluation for investment environment to provide investors and local government decision makers with more specific information on investment location. The aim of this study was to explain how to develop an analysis environment to support various investment researches and investors.

Corcoran et al. (1997) identified the optimal areas of location for the development of livestock enterprises within the European Union based on physical, climatic and socio-economic characteristics for areas being evaluated. Biermann (1998) presented the land suitability assessment methodology with multi-disciplinary data from different sources. The most appropriate location for low-income residential development was identified by integrating a wide range of data. Environmental or natural resources management decisions required the analysis of spatial information. GIS technologies had been used to facilitate decision making in many different fields. Tkach and Simonovic (1997) applied Compromise Programming technique within a GIS in order to evaluate floodplain for Red River Valley region in Manitoba, Canada. Antonie et al. (1997) presented an example application on integration of multicriteria evaluation technique with GIS for sustainable land use in Kenya; maximizing revenues from crop and livestock production, maximizing food output, maximizing district self-reliance in agricultural production, minimizing environmental damages from erosion. Thomas (2002) aimed to make brownfield sites competitive with undeveloped sites and returned these areas to productive uses by evaluating land use options with respect to brownfields inventory, characterization, and potential for redevelopment. Duijm and Markert (2002) searched the environmental impact and safety aspects for alternative scenarios for disposing of ammunition.

The main aim of this study is to generate a composite map for decision makers by using some effective factors causing flood. The study reviewed the role of GIS in decision-making and then outlined the evaluation approach for many criteria in decision process. The design of multicriteria environment attempted to use a variety of evaluation techniques to data from GIS and presented them in a manner familiar to decision makers. By integrating the evaluation techniques with GIS, it was intended that the effective factors would be evaluated more flexibly and thus more accurate decision would be made in a shorter time by the decision makers. By evaluating the criteria, the values of the criteria were classified to explain the opinions and preferences. Boolean and WLC approach were used in integrating MCE with GIS. The uncertain knowledge in multicriteria decision making was held by considering standardized criteria as fuzzy measures, where fuzzy set theory was emphasized. Different weights were given to the citeria in fuzzy extent with the Ordered Weighted Averaging (OWA) method. Finally all the composite maps created with these approaches were compared with the flooded area obtained from a hydraulic model.

2. METHODS

2.1 The General Outline

The flood vulnerability analysis applied in this study consists of two basic phases. Firstly, the effective factors causing floods are determined. Secondly several approaches to MCE in a GIS environment are applied and these approaches are evaluated in finding the flood vulnerable areas.

The evaluation procedure consists of the following steps:

1. *The assessment of a vulnerability structure*: choosing the effective factors and determining their importance and how they affect the flood vulnerability.
2. *Producing map layers*: raw data acquisition and transferring to appropriate GIS layers.
3. *Cartographic modeling*: defining the vulnerable areas using several approaches to MCE.
4. *Sensitivity analysis*: demonstrating the effect of different criterion weights on the spatial pattern of the vulnerable areas.

2.2 Assessment of A Vulnerability Structure

The first step in assessing the vulnerability structure is to determine the factors affecting the flood on the basis of an analysis of existing studies and knowledge. Here, judgments made by experts on hydrology and hydraulics can be applied. These factors are used as criterion separately. A criterion is a basis for a decision that can be measured and evaluated (Eastman et al., 1995). Layers representing the criteria are referred to as criterion maps.

2.3 Producing Map Layers

A GIS application is used for managing, producing, analyzing and combining spatial data. The data needed in this study are produced from collected or existing data by using different kinds of spatial functions and analysis.

2.4 Cartographic Modeling

Cartographic modeling is applied in producing and combining spatial data describing the causing factors. In the first phase, the vulnerable areas are produced by numerically overlaying a map layer describing the study area. This overlay is carried out as a Boolean overlay.

In the second phase ranking method is used. In Ranking Method, every criterion under consideration is ranked in the order of the decision maker's preference. To generate criterion values for each evaluation unit, each factor was weighted according to the estimated significance for causing flooding. The inverse ranking was applied to these factors. 1 is the least important and 8 is the most important factor as in Pramojanee et al. (2001). The criteria with their raw data were typically noncommensurate. To make the various criterion maps comparable, a standardization of the raw data was usually required (Malczewski, 1999a; Lin et al., 1997; Jiang and Eastman, 2000; Eastman et al., 1995). Linear Scale Transformation was adopted as a standardization procedure, because it is the most frequently used method for transforming the input data into commensurate scale. 0 is the worst-standardized score and 1 is the best-standardized score (Malczweski, 1999a). Through standardization, criterion scores were expressed according to a consistent numeric range, 0 and 1000, by multiplying with the constant number 1000. In fact, the aim was to get the range between 0 and 1, but GIS program accepted the calculation as only 0 and 1 as if it was a True/False evaluation. At the end of the standardization process, each factor had an equivalent measurement basis before any weights were applied.

In the third phase Pairwise Comparison Method is used in determining the weights for the criteria. This method involves the comparison of the criteria and allows the comparison of only two criteria at once. This method can convert subjective assessments of relative importance into a linear set of weights (Heywood et al., 1993). It was developed by Saaty (1980) in the context of a decision making process known as the Analytical Hierarchy Process

(AHP) (Malczewski, 1999a; Eastman et al., 1995; Malczewski, 1996). The criterion pairwise comparison matrix takes the pairwise comparisons as an input and produces the relative weights as output, and the AHP provides a mathematical method of translating this matrix into a vector of relative weights for the criteria. (Malczewski (1996) and Eastman et al. (1995) have evaluated this procedure very clearly.

A decision rule is a method of weighting or scoring criteria to assess their importance (Heywood et al., 1993). It is the procedure by which criteria are combined to arrive at a particular evaluation, and by which evaluations are compared and acted upon (Eastman et al., 1995). The aim of MADM analysis is to choose the best or the most preferred alternative. There are many decision rules that can be used in MCDM process. Weighted Linear Combination (WLC) is the most often used techniques for tackling spatial MADM and this approach was used as a decision rule in this study.

2.5 Sensitivity Analysis

The main purpose in sensitivity analysis is to examine how sensitive the choices are to the changes in criteria weights. This is useful in situations such as where uncertainties exist in the definition of the importance of different factors. Sensitivity analysis with examples can be found in Lowry et al. (1995).

3. CASE STUDY

3.1 Study Area

The West of Black Sea in the north of Turkey has the heavy local rains and snow melting, especially in springs. In this region, there are two main river basins: Filyos Basin and Bartın Basin. Being a floodprone area, Bartın is selected as the study area (Figure 3.1). It covers the subbasins of Ovacuma and Ulus Creeks, which are two of the upstream branches of Bartın River. Black Sea climate is dominant in the basin and heavy rainfall and variable plant cover are observed in the basin. The mean annual rainfall observed at Ulus meteorological station is 984.5 mm (Türkiye Akarsu Havzaları Taşkın Yıllığı, 1998).

3.2 Criteria Evaluation

For all criteria that are seen as map layer, the criterion values are generated. The causative factors for the flooding in every watershed like annual rainfall, size of watershed, basin slope, gradient of main drainage channel, drainage density, land use and the soil type were taken into account according to the literature surveys (Eimers et al., 2000; Henderson et al., 1996; and Pramojanee et al., 2001). The selected three criterion maps (drainage density, land use and soil type) are illustrated with their classification values in Figure 3.2. The original values can be found in Yalcin (2002).

3.3 Assigning Criteria Weights

The purpose of the criterion weighting is to express the importance of each criterion relative to other criteria. The more important criterion had the greater weight in the overall evaluation. In this study ranking method and pairwise comparison method were introduced and applied. The results were compared with the Boolean Overlay Approach. GIS should act as the interface between technology and the decision maker with integrating MCE methods into the GIS (Heywood et al., 1993). Different decision makers may apply different criterion and assign different weights for each criterion according to their preferences. The decision maker selects the criteria and compares them in a comparison matrix. The weights of the criteria and the consistency ratio of weighting procedure were calculated in interface module.

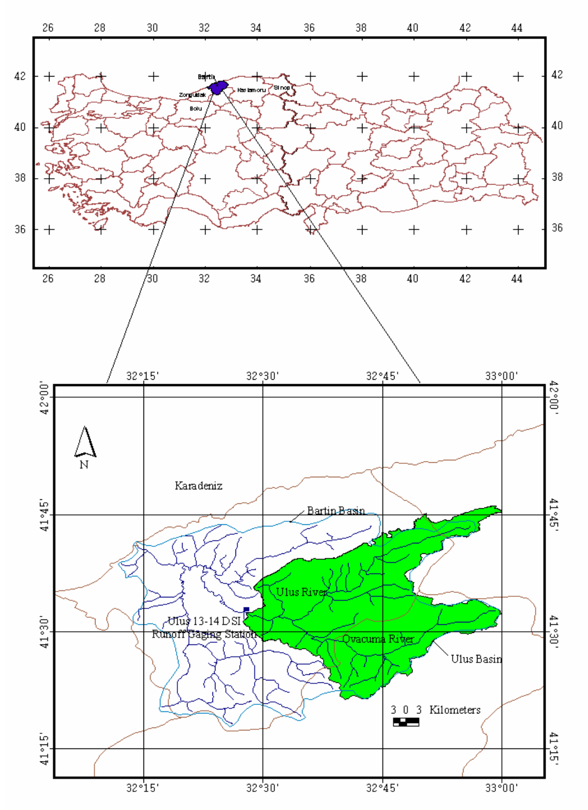

Figure 3.1: Study area.

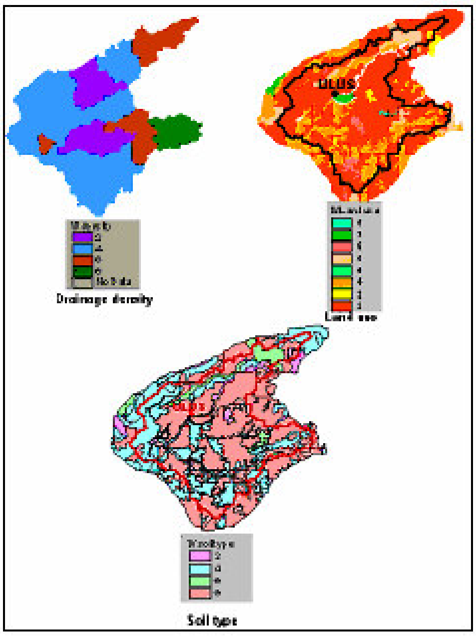

Figure 3.2: The selected three criterion maps with criterion values.

The criterion weights were calculated as 0.26, 0.21, 0.17, 0.16, 0.10, 0.06, and 0.04 respectively for annual rainfall, size of watershed, basin slope, gradient of main drainage channel, drainage density, land use and type of the soil. With the input values in pairwise comparison and weights calculated, consistency ratio (CR) was found as 0,042. This indicated a reasonable level of consistency in the pairwise comparison of the factors.

Three composite maps showing the flood vulnerable areas were created using multicriteria evaluation methods with GIS, namely Boolean Method and two WLC Methods are presented in Figures 3.3 - 3.5. The user interface was designed such that a decision maker could step through a weighting process with pairwise comparison that would result in the calculation.

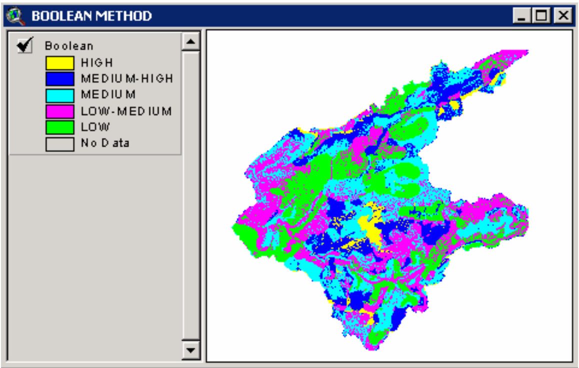

Figure 3.3: The final map that is created with Boolean Method.

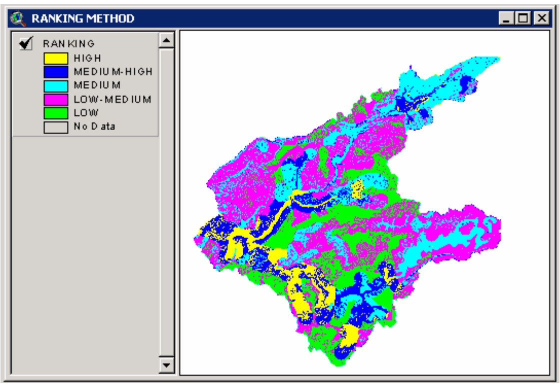

Figure 3.4: The final map that is created with Ranking Method.

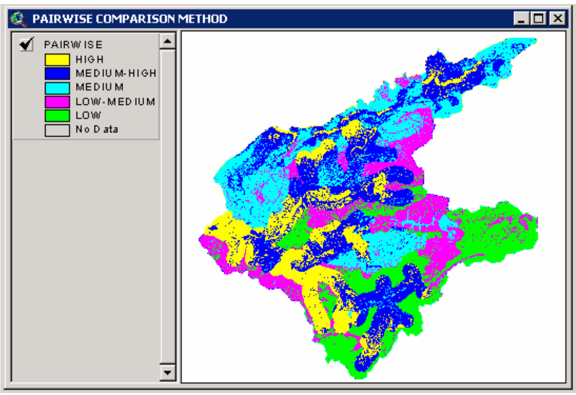

Figure 3.5: The final map that is created with PCM Method

This interface and the processes were presented in Figure 3.6. It involves: Viewing all criteria in a list box and each criteria pair in a matrix, Entering his or her preferences and ranks for each criteria pair, Calculating weights from the input ranks and preferences with Visual Basic Application VBA program embedded in GIS environment, Calculating consistency ratio on weights and input ranks, Modifying the ranks or preferences according to the user's choice.

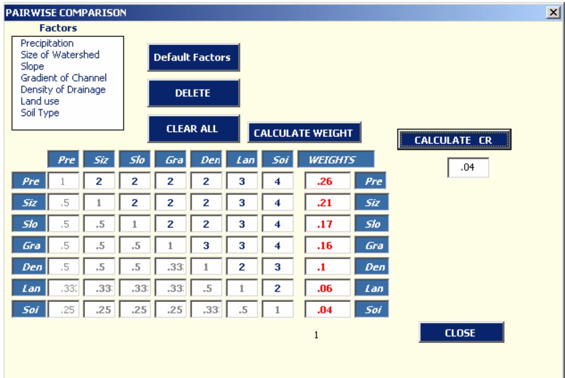

Figure 3.6: All calculations with weights and consistency ratio.

3.4 Fuzzy Measure Application in MCE

Zheng and Kainz (1999) have stated that uncertainty is endemic in GIS and it is best to draw attention to it because of its complexity and potentially damaging effects on decision making. The OWA decision rule is based on the principles of the fuzzy set aggregation (Malczewski. 1999a; Malczewski, 1999b). In GIS and decision making context, vulnerability was considered as a fuzzy concept expressed as a fuzzy set membership. Jiang and Eastman (2000) presented an example paper about suitability as a fuzzy concept. To rescale the range to a common numerical basis is unclear and involves fuzziness. The criteria were standardized to a common numeric range and then combined by weighted averaging. In WCL, criterion weights and ordered weights were used. Finally the illustrations gave an evaluation of vulnerability of flood hazard. The result of OWA method for MAX showed the most vulnerable areas and MIN showed the least vulnerable areas. AVERAGE fell midway between two extreme cases of fuzzy MIN and MAX operation and had a full tradeoff. Many other solutions were possible. The solutions were the effects of the distribution of risk and tradeoff. With this method, the aim was not to ignore the poor qualities, but they could be compensated for. Different illustrations give important idea to planners for location solutions. By compensating one criterion, decision maker can create different solutions.

3.5 Sensitivity Analysis

Sensitivity analysis depends on the error in the input data as criterion weights and criterion attributes. The sensitivity between the criteria basin slope and main channel gradient was analyzed. With addition of small perturbations to the weights for 10 cells, the ranking has changed for only one cell. This result indicates that those two criteria are not so sensitive for this analysis. When the sensitivity of criterion values was analyzed, it was also seen that there were no significant changes in the ranking with small perturbations on the gradient of the main channel criterion.

4. COMPARISON OF MCE APPROACHES

The criterion maps were combined by logical operators such as intersection and union in the Boolean approach. The vulnerable area distribution in the flooded area was compared with each other. To compare the methods (Ranking Method, Pairwise Comparison Method, Boolean Method), the percentages of the area in five classes namely; high, medium-high, medium, low-medium, low were calculated. The percentages gave a general idea about the vulnerability of the basin to the flood. Which method represents the closer zonation to the real flooded area? To answer these question the 100-year flood depth and area obtained by Usul et. al. (2002) was overlaid with the composite maps. According to the overlays the percentages were not similar to each other. It was obvious that the Boolean method was not suitable for analyzing the flood vulnerable areas. Because flood vulnerable areas, where flood was seen in the model outputs could not be obtained by Boolean approach. The results obtained with ranking method and especially with the pairwise comparison method were more suitable. Because the flooded area obtained by the model was also determined by pairwise comparison method.

By using fuzzy logic the error due to the standardization and classification of the values were reduced. The OWA method is an extension and generalization of the WLC method based on the uncertainty. It provides a consistent theoretical link between the two common MCE logics of Boolean overlay and WLC, and opens up the possibilities for aggregation of criteria. The poor qualities can be compensated for. The application of fuzzy measures in MCE in general and OWA in particular require further research.

After the flood vulnerable areas were determined, the areas at risk were obtained by overlaying the vulnerable areas with the cadastral parcels (Figure 4.1 and Figure 4.2). Determination of the areas at risk was needed for flood warning and floodplain development control. In order to represent the information of the parcel at risk, a database was created. Block Number, Parcel Number, total area of the parcel, flooded area, owner name-surname, address had been entered in the database.

5. CONCLUSION AND RECOMMENDATION

The flood vulnerable areas in the study area were evaluated in five classes. Since the methods take into account some example conditions of the region, the results can be as realistic only for this condition. When the characteristics change, the results will show the different conditions. The subjective numbers in the weights and the values of the criteria can be changed according to the study area characteristics and experts' opinions. Performing the sensitivity analysis on all the criterion weights, it was seen that the accuracy in estimating weights should be examined carefully. Sensitivity analysis helps to see if and how attribute and weight uncertainties play a role. Geographical sensitivity analysis is the study of how imposed perturbations of the inputs of geographical analysis affect the outputs of that analysis. The flood vulnerability maps can give planners, insurers and emergency services a valuable tool for assessing flood risk. Each of them needs to assess risk for more than one scenario. A project including these vulnerability maps should be used on land planning, use and management alternatives. The information in database should be obtained with an interface. In future this interface should be automatic in disaster related studies, because the amount of the insurance is needed to be calculated with the area under risk. The interface may be generated using a point-and-click operation window, with a reference map to navigate and highlight the area shown in the main map as in Sanders et al. (2000).

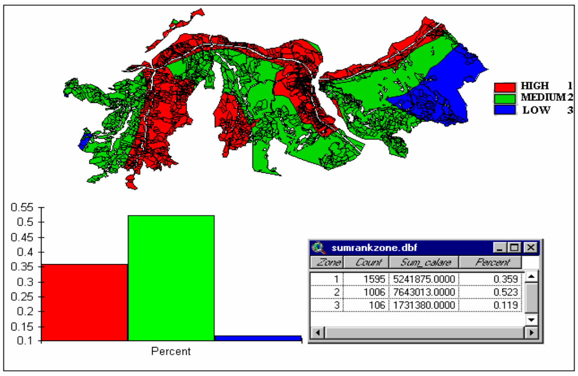

Figure 4.1: Areas under risk according to the risk degree and the percentage (Ranking Method).

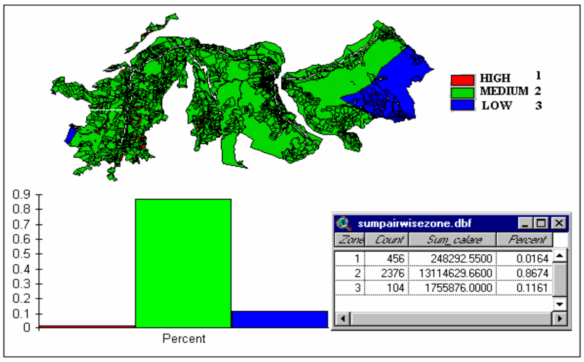

Figure 4.2: Areas under risk according to the risk degree and the percentage (Pairwise Comparison Method).

User interface allows users to evaluate and compare weights/alternatives and to speed up the calculation. For this kind of application, a required software program should be developed, new tools should be generated in the interface and the program with its interface and tools should be multi-user. The interface should provide query and drive all the necessary information. In the view of the total cost of flood, Flood Insurance Studies (FIS) must be strengthened and National Flood Insurance Program (NFIP) must be established by the national flood insurance acts. Flood Insurance Rate Map (FIRM) should be produced for the private insurance industry and the state. This map should provide the divides for the area studied into flood hazard zones that are used to establish insurance rates.

Some arrangements must be developed and evaluated to deal with the problems:

- The flood vulnerable areas should not be in the concept of ownership. They should be in the authority and the possession (use) of the state and counted as ownerless land such as parks, areas between the coast-edge lines.
- A wide region should be considered in the concept of rural area arrangements. The arrangement should be done through

the non-vulnerable areas. The vulnerable areas should be out of the arrangement.

- If the flood prone area cannot be expropriated, especially because of the economic reasons, the vulnerable areas might be evaluated in the concept of Arrangement Partnership Part. Thus, 35 per cent of the total area is left directly and can be used as green area. The area in the arrangement can be provided by the exchange of the treasure goods instead of expropriation.
- Aforestation on the area which is left as green part during the arrangement is one of the most favorable method to mitigate the risk on the flood vulnerable area. In addition, special conditions might be applied on these areas by proposal of Ministry of Agriculture and by compulsion of Province Public Works Directorate.

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