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Robust spatial flood vulnerability assessment for Han River using fuzzy TOPSIS with α-cut level set

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ABSTRACT

This study aims to improve the general flood vulnerability approach using fuzzy TOPSIS based on α-cut level sets which can reduce the uncertainty inherent in even fuzzy multi-criteria decision making process. Since fuzzy TOPSIS leads to a crisp closeness for each alternative, it is frequently argued that fuzzy weights and fuzzy ratings should be in fuzzy relative closeness. Therefore, this study used a modified α-cut level set based fuzzy TOPSIS to develop a spatial flood vulnerability approach for Han River in Korea, considering various uncertainties in weights derivation and crisp data aggregation. Two results from fuzzy TOPSIS and modified fuzzy TOPSIS were compared. Some regions which showed no or small ranking changes have their centro-symmetric distributions, while other regions whose rankings varied dynamically, have biased (anti-symmetric) distributions. It can be concluded that α-cut level set based fuzzy TOPSIS produce more robust prioritization since more uncertainties can be considered. This method can be applied to robust spatial vulnerability or decision making in water resources management.

1. Introduction

River, coastal and flash floods can claim human lives, destroy properties, damage economies, make fertile land unusable and damage the environment. The development of techniques, measures and assessment methodologies to increase understanding of flood risk or vulnerability can assist decision makers greatly in reducing damage and fatalities. Different methods to assess risk and vulnerability of areas to flooding have been developed over the last few decades.

However, the term "risk" in relation to flood hazards was introduced by Knight (1921), and is used in diverse different contexts and topics showing how adaptive any definition can be (Sayers et al., 2011). Smith (2004) considered risk as the product of two components, i.e., probability and consequence. This concept of flood risk is strictly related to the probability that a high flow event of a given magnitude occurs, which results in consequences which span environmental, economic and social losses caused by that event. This deterministic approach use physically based modeling methods to estimate flood hazard/probability of particular event, coupled with damage assessment models which estimate economic consequence to provide an assessment of flood risk in an area (Balica, Popescu, Beevers, & Wright, 2013).

On the other hand, after many discussions and disputes, the term "vulnerability" can be commonly understood that vulnerability is the degree to which a system is susceptible to, or unable to cope with the adverse effects of environmental changes (IPCC, 2001). In relation to hazards and disasters, vulnerability is a concept that links the relationship that people have with their environment to social forces and institutions, as well as the cultural values that sustain and contest them. The concept of vulnerability expresses the multidimensionality of disasters by focusing attention on the totality of relationships in a given social situation. These relationships, together with environmental forces, are capable of producing a disaster prevention plan (Frerks, Bankoff, & Hilhorst, 2004). Vulnerability also refers to the extent to which changes could harm a system, or to which a community can be affected by the impact of a hazard. Therefore, this parametric approach aims to use readily available data of information to build a picture of the vulnerability of an area (Balica, Popescu, Beevers, & Wright, 2013).

Although each of these approaches has advantages and disadvantages for decision makers, this study used the parametric vulnerability which has been increasingly accepted since it is coupled with climate change approach to disaster in recent years.

Parametric vulnerability research generally consists of various sub-topics such as indicator selection, weight determination and assessment methodology (Moel, Alphen, & Aerts, 2009; RPA, 2004; Akter & Simonovic, 2005; Thinh & Vogel, 2006; Meyer, Scheuer, & Haase, 2009; Chung & Lee, 2009; Sebald, 2010; Chung,

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Hong, Lee, & Burian, 2011; Jun, Chung, Kim, & Kim, 2011, 2012). That is, parametric vulnerability approach is quite similar to the general multi-criteria decision-making (MCDM) method.

However, although MCDM is suitable for decision-making in flood vulnerability, MCDM is very difficult to exactly be applied since the data for flood vulnerability closely related to social, economic and environmental circumstances have high uncertainty. Therefore, the flood vulnerability assessment should consider lots of uncertainties, such as the uncertainty of weights and proxy variables' crisp data. Thus, Simonovic and Niruoama (2005) combined MCDM method and fuzzy set theory to address various uncertainties in water resources management. Fuzzy MCDM methods to reduce the uncertainty of parametric approach inherent in the processes of weights determination and derivation of crisp input data have used in the various fields such as reservoir operation (Fu, 2008; Afshar, Mariño, Saadatpour, & Afsahr, 2011), groundwater vulnerability (Zhou, Wang, & Yang, 1999), group decision making (Shih, Shyur, & Lee, 2007), airline industry (Torlak, Sevkli, Sanal, & Zaim, 2011), tourism (Tsaur, Chang, & Yen, 2002), plant location selection (Chu, 2002), water resources vulnerability (Kim & Chung, 2013) and flood vulnerability (Sebald, 2010; Lee, Jun, & Chung, 2013).

Even fuzzy MCDM approaches, however, lead to a crisp relative closeness for each alternative. Thus, it is continuously, argued fuzzy weights and fuzzy ratings should result in fuzzy relative closeness. Crisp relative closeness provides only one possible solution to a fuzzy MCDM problem, but cannot reflect the whole picture of its all possible solutions. In spite of the fact that fuzzy TOPSIS (technique for order preference by similarity to an ideal solution; Hwang & Yoon, 1981) offers a fuzzy relative closeness for each alternative (Triantaphyllou & Lin; 1996; Kang, Lee, Chung, Kim, & Kim, 2013), the closeness is badly distorted and over exaggerated because of the reason of fuzzy arithmetic operations. Therefore, Wang and Elhag (2006) developed a fuzzy TOPSIS method based on α level sets and the fuzzy extension principle, which turns out to be a nonlinear programming problem. This also used an α-level set based fuzzy TOPSIS to develop a flood vulnerability approach for Han River in Korea, considering various uncertainties in the fuzzy MCDM process.

2. Methodology

2.1. Fuzzy set theory with α level sets

A fuzzy set theory is a powerful mathematical tool for handling uncertainty in decision making. A fuzzy set is a general form of a crisp set. A fuzzy number takes on values in the closed interval 0 and 1, in which 1 represents full membership and 0 represents non-membership. In contrast, crisp sets only allow values of 0 or 1. There are different types of fuzzy numbers that can be utilized, depending on the situation. It is often convenient to work with TFNs because they are relatively simple to compute and are useful for representing and processing information in a fuzzy environment.

(1) Triangular fuzzy numbers (TFNs)
A fuzzy number, $\widetilde{A}$, on R can be a TFN if its membership function, $\mu\widetilde{A}(x) : R \to [0,1]$, can be defined as follows:

$$\mu_{\widetilde{A}} = \begin{cases} 0, & x \leqslant a \\ \frac{x-a}{b-a}, & a \leqslant x \leq b \\ \frac{c-x}{c-b}, & b \leqslant x \leq c \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

(2) Multiplication of TFNs
Suppose that we have two TFNs $\widetilde{A}$ and $\widetilde{B}$ such that $\widetilde{A} = (a_1, a_2, a_3)$ and $\widetilde{B} = (b_1, b_2, b_3)$ then, the multiplication of the fuzzy numbers $\widetilde{A}$ and $\widetilde{B}$ is defined as follows:

$$\widetilde{A} \oplus \widetilde{B} = (a_1 + b_1, a_2 + b_2, a_3 + b_3) \tag{2}$$

$$\widetilde{A} \ominus \widetilde{B} = (a_1 - b_1, a_2 - b_2, a_3 - b_3) \tag{3}$$

$$\widetilde{A} \odot \widetilde{B} = (a_1 b_1, a_2 b_2, a_3 b_3) \tag{4}$$

Let $\widetilde{A} = (a_1, a_2, a_3)$ and $\widetilde{B} = (b_1, b_2, b_3)$ be two TFNs, then the distance between them using vertex method is defined as (Chen, 2000)

$$d(\widetilde{A}, \widetilde{B}) = \sqrt{\frac{1}{3}\left[(a_1 - b_1)^2 + (a_2 - b_2)^2 + (a_3 - b_3)^2\right]} \tag{4}$$

(3) α-cut level set
The α-cut of fuzzy number A can be defined as (Kaufmann & Gupta, 1991):

$$(\widetilde{A})_\alpha = \{x | f_a(x) \geq \alpha\} \tag{5}$$

where $x \in R, a \in [0,1]$.

$(\widetilde{A})_\alpha$ is a non-empty bounded closed interval contained in R and it can be denoted by $(\widetilde{A})_\alpha = [(a)_{\alpha^L}, (a)^U_\alpha]$, where $(a)^L_\alpha$ and $(a)^U_\alpha$ are the lower and upper bounds of the closed interval, respectively.

For example, if a TFN $\widetilde{A} = (1, m, n)$, then the α-cut of A can be expressed as:

$$(\widetilde{A})_\alpha = [(a)^L_\alpha, (a)^U_\alpha)] = [(m - l)\alpha + l, -(u - m)\alpha + u]. \tag{6}$$

Given fuzzy numbers A and B, $A, B \in R^+$, the α-cuts of A and B are $(A) = [(a)^L_\alpha, (a)^U_\alpha]$ and $(A) = [(b)^L_\alpha, (b)^U_\alpha]$, respectively. By interval arithmetic, some main operations of A and B can be expressed as follows:

$$(A \oplus B)_\alpha = [(a)^L_\alpha + (b)^L_\alpha, (a)^U_\alpha + (b)^U_\alpha)] \tag{7}$$

$$(A \ominus B)_\alpha = [(a)^L_\alpha - (b)^L_\alpha, (a)^U_\alpha - (b)^U_\alpha)] \tag{8}$$

$$(A \otimes B)_\alpha = [(a)^L_\alpha (b)^L_\alpha, (a)^U_\alpha (b)^U_\alpha)] \tag{9}$$

2.2. TOPSIS method

TOPSIS, known as one of the most classical MCDM methods, is based on the idea, that the chosen alternative should have the shortest distance from the positive ideal solution and on the other side the farthest distance of the negative ideal solution (Hwang & Yoon, 1981: Lai, Liu, & Hwang, 1994). The technique is based on the concept that the ideal alternative has the best level for all attributes, whereas the negative ideal is the alternative with all of the worst attribute values. A TOPSIS solution is defined as the alternative that is simultaneously farthest from the negative ideal and closest to the ideal alternative (Chu, 2002). According to Kim, Park, and Yoon (1997) and Shih, Shyur and Lee (2007), there are four advantages of using TOPSIS: (1) a sound logic that represents the rationale of human choice; (2) a scalar value that accounts for both the best and worst alternatives simultaneously; (3) a simple computation process that can be easily programmed; and (4) for any two dimensions, the performance measures for all alternatives can be visualized on a polyhedron.

The procedure of TOPSIS can be expressed in a series of steps:

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(1) Calculate the normalized decision matrix. The normalized value n_{ij} is calculated as

$$n_{ij} = x_{ij} \Big/ \sqrt{\sum_{i=1}^{m} x_{ij}^2}, \quad i = 1, \ldots, m, \; j = 1, \ldots, n \tag{10}$$

(2) Calculate the weighted normalized decision matrix. The weighted normalized value v_{ij} is calculated as

$$r_{ij} = w_j n_{ij}, \quad i = 1, \ldots, m, \; j = 1, \ldots, n \tag{11}$$

where w_j is the weight of the ith attribute or criterion, and $\sum_{j=1}^{n} w_j = 1$.

(3) Determine the positive ideal and negative ideal solution

$$A^+ = \{r_1^+, \ldots, r_n^+\} = \left\{ (\max_j r_{ij} | i \in I), (\min_j r_{ij} | i \in J) \right\} \tag{12}$$

$$A^- = \{r_1^-, \ldots, r_n^-\} = \left\{ (\min_j r_{ij} | i \in I), (\max_j r_{ij} | i \in J) \right\} \tag{13}$$

where I is associated with benefit criteria, and J is associated with cost criteria.

(4) Calculate the separation measures, using the n-dimensional Euclidean distance. The separation of each alternative from the ideal solution is given as

$$d_j^+ = \left[\sum_{j=1}^{n} (r_{ij} - r_j^+)^2 \right]^{1/2}, \quad i = 1, \ldots, m \tag{14}$$

$$d_j^+ = \left[\sum_{j=1}^{n} (r_{ij} - r_j^-)^2 \right]^{1/2}, \quad i = 1, \ldots, m \tag{15}$$

(5) Calculate the relative closeness to the ideal solution. The relative closeness of the alternative A_i with respect to A^+ is defined as

$$R_j = \frac{(d_j^-)}{(d_j^+) + (d_j^-)}, \quad i = 1, \ldots, m. \tag{16}$$

(6) Rank the preference order. For ranking alternatives using this index, we can rank alternatives in decreasing order.

The basic principle of the TOPSIS method is that the chosen alternative should have the "shortest distance" from the positive ideal solution and the "farthest distance" from the negative ideal solution. The TOPSIS method introduces two "reference" points, but it does not consider the relative importance of the distances from these points.

2.3. α-Level based fuzzy TOPSIS

Wang and Elhag (2006) suggest a fuzzy TOPSIS method based on α-cut level sets and presents a nonlinear programming (NLP) solution procedure. It is shown that the proposed fuzzy TOPSIS method performs better than the other fuzzy versions of the TOPSIS method. This approach is a major motivation for robust spatial flood vulnerability estimation in this study.

To consider fuzziness, as opposed to crisp data, values in D (the performance matrix) and W are presented as shown in Eqs. (17) and (18), respectively (Afshar, Mariño, Saadatpour, & Afsahr, 2011; Jun, Chung, Kim, & Kim, 2012).

$$\widetilde{D} = [\tilde{x}_{ij}] \tag{17}$$

$$\widetilde{W} = [\widetilde{W}_i] \tag{18}$$

Where $\tilde{x}_{i,j}$ represents the fuzzy rating of alternatives A_j with respect to criterion C_i and $\widetilde{W}_i$ represents the fuzzy weight for criterion C_i. In the absence of a reliable probability distribution function, an intuitively easy, effective, and commonly used approach that accounts for the uncertainty of the value of an unknown parameter is a TFN, $\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij})$.

The fuzzy performance matrix is formed by arraying columns of criteria with rows of alternative, as shown below.

$$\widetilde{W} = \begin{bmatrix} \tilde{x_{11}} & \tilde{x_{12}} & \ldots & \tilde{x_{1n}} \\ \tilde{x_{21}} & \tilde{x_{22}} & \ldots & \tilde{x_{2n}} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{x_{m1}} & \tilde{x_{m2}} & \ldots & \tilde{x_{mn}} \end{bmatrix} \tag{19}$$

The performance matrix should be normalized to convert the values of weighted alternative into a common dimensionless unit for comparison. Normalized performance, $\tilde{x}_{ij}$, can be obtained using the following transformation formulae for benefit and cost criteria:

$$c_j^* = \max_i d_{ij}, \quad j \in \Omega_b \tag{20}$$

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*} \right), \quad j \in \Omega_b \tag{21}$$

$$a_j^- = \min_i a_{ij}, \quad j \in \Omega_c \tag{22}$$

$$\tilde{r}_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}} \right), \quad j \in \Omega_c \tag{23}$$

Determine the ideal solution and the negative ideal solution by Eqs. (24) and (25) if necessary.

$$A^+ = \{x_1^+, \ldots, x_m^+\} \tag{24}$$

$$A^- = \{x_1^-, \ldots, x_m^-\} \tag{25}$$

Calculate the α-cut level sets of r_{ij} or w_j ($i = 1, \ldots, n$; $j = 1, \ldots, m$) by setting different α levels.

$$(r_{ij})_\alpha = [(r_{ij})_\alpha^L, (r_{ij})_\alpha^U)] \tag{26}$$

$$(w_{ij})_\alpha = [(w_{ij})_\alpha^L, (w_{ij})_\alpha^U)] \tag{27}$$

Compute the fuzzy relative closeness of each alternative by solving the NLP models (28) and (29) for each α-cut level.

$$(\mathrm{RC}_i)_\alpha^L = \min \frac{\sqrt{\sum_{j=1}^{m} (w_j (r_{ij})_\alpha^L)^2}}{\sqrt{\sum_{j=1}^{m} (w_j (r_{ij})_\alpha^L)^2} + \sum_{j=1}^{m} (w_j (r_{ij})_\alpha^L - 1)^2} \tag{28}$$

$$(\mathrm{RC}_i)_\alpha^U = \max \frac{\sqrt{\sum_{j=1}^{m} (w_j (r_{ij})_\alpha^U)^2}}{\sqrt{\sum_{j=1}^{m} (w_j (r_{ij})_\alpha^U)^2} + \sum_{j=1}^{m} (w_j (r_{ij})_\alpha^U - 1)^2} \tag{29}$$

s.t. $(w_j)_\alpha^L \leqslant w_j \leqslant (w_j)_\alpha^U, \; j = 1, \ldots, m$

Defuzzify the fuzzy relative closeness by Eq. (30).

$$(\mathrm{RC}_i)_{ALC}^* = \frac{1}{N} \sum_{j=1}^{N} \left(\frac{(RC_i)_{\alpha_j}^L + (RC_i)_{\alpha_j}^U}{2} \right), \quad i = 1, \ldots, n \tag{30}$$

Rank alternatives in terms of their defuzzified relative closenesses.

2.4. Procedure

This study consists of six steps as shown in Fig. 1. Step 1 is to select all feasible proxy variables or indicators to quantify, mea-

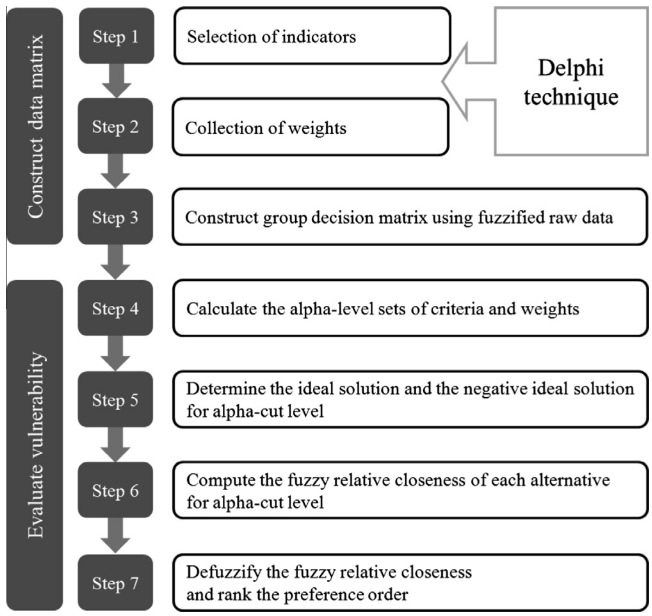

Fig. 1. Flood vulnerability assessment procure using fuzzy TOPSIS with alpha cut level.

sure, and communicate relevant information. Proxy variables are necessary since this process is complex concepts that cannot be directly measured or observed (Hamouda, Nour El-Din, & Moursy, 2009). These variables should simplify or summarize a number of important properties, rather than focus on isolated characteristics of a system. In addition, indicators must be measurable, or at least observable, and the methodology used to construct them should be transparent and understandable (Seager, 2001). Step 2 is to derive all weights on proxy variables using an objective procedure. Since steps 1 and 2 are cross-related, this study used Delphi technique to select all criteria and quantify all weights. Delphi technique is a method for structuring a group communication process so that the process is effective in allowing a group of individuals (Linstone & Turoff, 1975). This study used the preceding research results (Lee, Jun, & Chung, 2013) for step 1 and 2. Thus, those results are included in brief. Step 3 is to collect all data and construct TFNs of all study regions to all proxy variables. TFNs were derived from each probability density function using R-statistic software. An example is shown in Fig. 3. Then step 4 is to modify the TFNs based on α level sets. This study varied the α values from 0.0 to 1.0 by 0.1. Step 5 is to determine the ideal solution and the negative ideal solutions based on Eqs. (28) and (29) using a nonlinear programming solution technique. Step 6 is to compute the fuzzy closeness of each alternative and step 7 is to defuzzify the relative closeness using Eq. (30) and rank the preference order.

3. Study region

The downstream area of Han River was selected in this study. The Han River basin is located in the middle of the Korean peninsula and includes Seoul, the capital of South Korea. The Han River consists of two major tributaries (the NHR and SHR) and many small tributaries. It drains an area of 26,018 km^2 or 27% of South Korea and is 5417 km long. The annual discharge varies between 16.0 and 18.9 km^3. The river originates at an altitude of more than 1300 m above sea level in the Taeback Mountains, and traverses

Fig. 2. Study area and sub-region map: the downstream region of the Han River.

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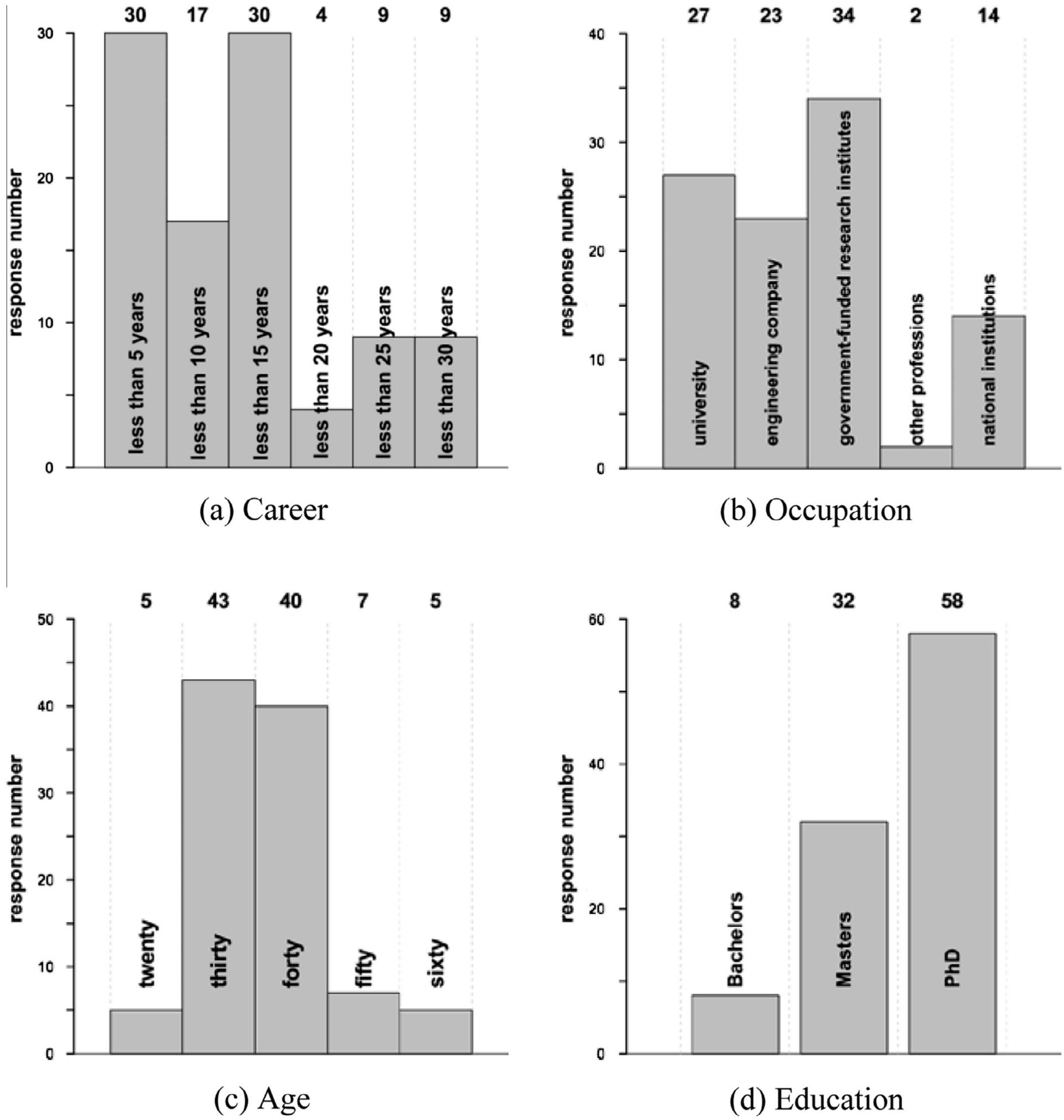

Fig. 3. Basic information for respondents.

the mid-western parts of the Korean Peninsula before flowing into the Yellow Sea. Much of the river catchments are in mountainous terrain. The two tributaries of the Han River join at the Paldang dam, forming the main channel (Fig. 3). The Paldang dam is the first reservoir located on the main river channel and serves as a starting point in this study. The climate of the study area is temperate with four different seasons. The monthly average temperatures in the study area varied from −2.5 °C in January to +25.4 °C in August. The 30-year (1971–2000) average annual precipitation is 1344 mm, and about two-thirds of the annual precipitation occurs between June and September (Korea Meteorological Administration, website: www.kma.go.kr).

The downstream of Han River have suffered from flood damage frequently and thus have invested tremendous budget to mitigation and restoration projects. Especially, heavy rainfall in the study region in late July 2011 triggered a series of flash flood (495 mm of rain during a two-day span) and landslides that killed at least 49 people by July 27, leaving a total of more than 77 dead or missing. On July 27, the number of killed rose further to 69. At least 86 power outages followed the landslides, affecting 125,000 people by July 27. Over 11,000 South Koreans were forced to evacuate.

Therefore, 17 sub-regions adjacent to Han River shown in Fig. 2 were derived based on the administrative districts since each local government has a responsibility to mitigate and restore the flood damage. They are regarded as alternatives in this decision making problem. The region shown in Fig. 2 is the hottest place for flood damage mitigation and prevention in the Han River basin as well as South Korea.

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4. Results

4.1. Selection of proxy variables

The Delphi process was used to build a consensus on the selection of appropriate indicators and estimate their weights. The success of the Delphi study clearly rested on the combined expertise of the participants who made up the expert panel. There were two key aspects, (1) the panel size and (2) qualifications of the experts. Thus, the panel size in this research was planned to be greater than 40. Further, although the panel members in our research are working toward or had worked toward flood risk management, they came from the following different sectors: (1) government, (2) private companies, (3) research centers, and (4) educational institutions. Thus, it was expected that various opinions with diverse perspectives would arise. The interviewees were surveyed individually.

44 flood risk management experts participated in the panel. 15 (34%) of 44 had been engaged in government-funded research at institutes and 12 (27%) had conducted research at a university. 10 (23%) had worked in engineering companies, and 6 (14%) had been civil servants working for national institutions. Only one

Table 1
A decision group of criteria.

Character	Alternative (source year)	Weight FTNs
Social		(0.16,0.36,0.55)
	Population growth (2012)	(0.10,0.25,046)
	Population (2012)	(0.14,0.30,0.49)
	Metropolitan area (2012)	(0.09,0.21,0.41)
	Annual average flood victims (1971–2006)	(0.14,0.32,0.55)
	Annual average flood casualties (1971–2006)	(0.23,0.44,0.68)
	Local government competence (2012)	(0.04,0.13,0.30)
Economic		(0.30,0.54,0.69)
	Establishments (2012)	(0.06,0.18,0.22)
	The labor force participation rate (2012)	(0.15,0.31,0.39)
	Average cost of land (2008)	(0.13,0.29,0.48)
	Annual average flood damage (1971–2006)	(0.30,0.52,0.71)
	Annual maximum flood damage (1971–2006)	(0.30,0.55,0.73)
Hydrological		(0.74,0.93,0.95)
	Maximum inundation area (1971–2006)	(0.21,0.45,0.64)
	200-year frequency flood	(0.14,0.29,0.50)
	Maximum flood (2005–2010)	(0.19,0.39,0.63)
	200-year flood inundation area	(0.22,0.42,0.65)
	Flood defense facilities (1971–2006)	(0.07,0.19,0.38)

Table 2
Fuzzified raw data for flood vulnerability assessment.

Alternative		Criteria							
		Population growth	Population	Metropolitan area	Annual average flood victims	Annual average flood casualties	Local government competence	Establishments	The labor force participation rate
Left bank	1	(0.10,0.25,0.46)	(0.02,0.05,0.07)	(0.02,0.05,0.10)	(0.00,0.00,0.00)	(0.04,0.07,0.11)	(0.02,0.06,0.13)	(0.00,0.00,0.00)	(0.04,0.09,0.11)
	2	(0.01,0.03,0.05)	(0.03,0.05,0.08)	(0.00,0.00,0.00)	(0.00,0.01,0.02)	(0.03,0.05,0.08)	(0.01,0.02,0.04)	(0.01,0.03,0.04)	(0.04,0.08,0.10)
	3	(0.02,0.05,0.09)	(0.10,0.19,0.30)	(0.09,0.21,0.41)	(0.04,0.09,0.15)	(0.12,0.22,0.35)	(0.02,0.05,0.13)	(0.02,0.07,0.08)	(0.02,0.04,0.05)
	4	(0.02,0.06,0.10)	(0.07,0.13,0.21)	(0.09,0.21,0.41)	(0.08,0.17,0.29)	(0.13,0.25,0.39)	(0.04,0.13,0.30)	(0.02,0.08,0.09)	(0.05,0.11,0.14)
	5	(0.00,0.00,0.00)	(0.08,0.14,0.23)	(0.09,0.21,0.41)	(0.14,0.32,0.55)	(0.12,0.23,0.36)	(0.03,0.08,0.19)	(0.02,0.07,0.08)	(0.03,0.07,0.08)
	6	(0.00,0.01,0.02)	(0.12,0.22,0.35)	(0.09,0.21,0.41)	(0.05,0.11,0.20)	(0.07,0.14,0.22)	(0.01,0.04,0.10)	(0.02,0.06,0.07)	(0.04,0.08,0.10)
	7	(0.00,0.00,0.01)	(0.01,0.02,0.03)	(0.01,0.02,0.03)	(0.01,0.03,0.05)	(0.06,0.11,0.17)	(0.02,0.05,0.12)	(0.01,0.03,0.04)	(0.15,0.31,0.39)
	8	(0.08,0.19,0.34)	(0.00,0.00,0.01)	(0.00,0.01,0.02)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.01,0.03,0.06)	(0.00,0.01,0.01)	(0.02,0.05,0.06)
Right bank	9	(0.06,0.14,0.25)	(0.01,0.02,0.03)	(0.04,0.09,0.17)	(0.00,0.00,0.00)	(0.13,0.26,0.40)	(0.02,0.07,0.15)	(0.00,0.00,0.00)	(0.02,0.03,0.04)
	10	(0.00,0.00,0.00)	(0.08,0.15,0.23)	(0.09,0.21,0.41)	(0.03,0.07,0.12)	(0.03,0.06,0.10)	(0.00,0.01,0.03)	(0.01,0.04,0.05)	(0.02,0.03,0.04)
	11	(0.01,0.02,0.03)	(0.03,0.06,0.10)	(0.09,0.21,0.41)	(0.05,0.11,0.18)	(0.23,0.44,0.68)	(0.02,0.05,0.12)	(0.02,0.07,0.09)	(0.12,0.24,0.30)
	12	(0.01,0.03,0.06)	(0.16,0.30,0.47)	(0.09,0.21,0.41)	(0.06,0.14,0.24)	(0.02,0.03,0.05)	(0.01,0.05,0.11)	(0.02,0.06,0.07)	(0.02,0.05,0.06)
	13	(0.02,0.05,0.09)	(0.08,0.14,0.23)	(0.09,0.21,0.41)	(0.03,0.06,0.10)	(0.16,0.30,0.46)	(0.01,0.04,0.10)	(0.04,0.13,0.16)	(0.02,0.04,0.05)
	14	(0.01,0.03,0.05)	(0.12,0.22,0.33)	(0.09,0.21,0.41)	(0.04,0.09,0.16)	(0.20,0.38,0.59)	(0.01,0.02,0.04)	(0.06,0.18,0.22)	(0.00,0.00,0.00)
	15	(0.00,0.01,0.02)	(0.11,0.21,0.32)	(0.09,0.21,0.41)	(0.05,0.12,0.20)	(0.06,0.11,0.17)	(0.00,0.00,0.00)	(0.03,0.11,0.13)	(0.02,0.04,0.05)
	16	(0.01,0.03,0.06)	(0.15,0.28,0.45)	(0.09,0.21,0.41)	(0.04,0.09,0.16)	(0.05,0.09,0.14)	(0.01,0.02,0.04)	(0.02,0.08,0.09)	(0.04,0.08,0.10)
	17	(0.01,0.03,0.05)	(0.06,0.11,0.17)	(0.02,0.06,0.11)	(0.00,0.00,0.00)	(0.09,0.17,0.27)	(0.03,0.09,0.21)	(0.01,0.04,0.05)	(0.02,0.03,0.04)

Alternative		Criteria							
		Average cost of land	Annual average flood damage	Annual maximum flood damage	Maximum inundation area	200-year frequency flood	maximum flood	200-year flood inundation area	flood defense facilities
Left bank	1	(0.04,0.08,0.14)	(0.08,0.15,0.20)	(0.12,0.22,0.29)	(0.08,0.16,0.23)	(0.10,0.22,0.36)	(0.17,0.35,0.56)	(0.02,0.04,0.06)	(0.00,0.00,0.00)
	2	(0.04,0.09,0.14)	(0.16,0.28,0.38)	(0.09,0.16,0.22)	(0.09,0.18,0.26)	(0.12,0.26,0.44)	(0.17,0.35,0.57)	(0.00,0.00,0.00)	(0.00,0.00,0.00)
	3	(0.02,0.04,0.07)	(0.30,0.52,0.71)	(0.09,0.16,0.21)	(0.13,0.26,0.38)	(0.13,0.28,0.48)	(0.18,0.36,0.58)	(0.00,0.00,0.00)	(0.07,0.19,0.38)
	4	(0.08,0.17,0.29)	(0.07,0.13,0.17)	(0.04,0.08,0.11)	(0.00,0.00,0.00)	(0.14,0.29,0.50)	(0.19,0.39,0.63)	(0.00,0.00,0.00)	(0.02,0.05,0.10)
	5	(0.03,0.06,0.10)	(0.05,0.09,0.13)	(0.00,0.00,0.00)	(0.06,0.13,0.19)	(0.14,0.29,0.50)	(0.16,0.33,0.53)	(0.00,0.00,0.00)	(0.05,0.13,0.27)
	6	(0.03,0.06,0.10)	(0.05,0.09,0.13)	(0.00,0.00,0.00)	(0.06,0.13,0.19)	(0.00,0.01,0.01)	(0.00,0.01,0.01)	(0.00,0.00,0.00)	(0.02,0.05,0.10)
	7	(0.13,0.29,0.48)	(0.00,0.00,0.00)	(0.00,0.00,0.01)	(0.02,0.05,0.08)	(0.00,0.01,0.01)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)
	8	(0.02,0.04,0.07)	(0.02,0.03,0.04)	(0.05,0.09,0.12)	(0.01,0.02,0.03)	(0.00,0.00,0.00)	(0.00,0.01,0.01)	(0.00,0.00,0.00)	(0.00,0.00,0.00)
Right bank	9	(0.01,0.02,0.03)	(0.04,0.07,0.10)	(0.02,0.04,0.06)	(0.18,0.38,0.55)	(0.11,0.23,0.40)	(0.17,0.34,0.55)	(0.22,0.42,0.65)	(0.00,0.00,0.00)
	10	(0.01,0.01,0.03)	(0.21,0.36,0.49)	(0.14,0.25,0.33)	(0.16,0.34,0.49)	(0.13,0.27,0.46)	(0.18,0.37,0.59)	(0.00,0.00,0.00)	(0.03,0.07,0.15)
	11	(0.12,0.26,0.44)	(0.11,0.19,0.26)	(0.08,0.14,0.19)	(0.06,0.12,0.17)	(0.13,0.28,0.48)	(0.18,0.36,0.58)	(0.00,0.00,0.00)	(0.03,0.07,0.14)
	12	(0.03,0.06,0.11)	(0.05,0.09,0.12)	(0.09,0.16,0.22)	(0.06,0.13,0.19)	(0.14,0.29,0.50)	(0.19,0.39,0.63)	(0.00,0.00,0.00)	(0.01,0.01,0.03)
	13	(0.01,0.03,0.04)	(0.07,0.12,0.16)	(0.30,0.55,0.73)	(0.08,0.16,0.23)	(0.14,0.29,0.50)	(0.19,0.39,0.63)	(0.00,0.00,0.00)	(0.01,0.02,0.03)
	14	(0.00,0.00,0.00)	(0.04,0.08,0.11)	(0.19,0.34,0.45)	(0.07,0.15,0.21)	(0.14,0.29,0.50)	(0.16,0.33,0.53)	(0.00,0.00,0.00)	(0.01,0.03,0.05)
	15	(0.02,0.05,0.09)	(0.06,0.11,0.15)	(0.07,0.14,0.18)	(0.07,0.15,0.21)	(0.00,0.01,0.01)	(0.00,0.01,0.01)	(0.00,0.00,0.00)	(0.05,0.13,0.26)
	16	(0.03,0.06,0.11)	(0.08,0.15,0.20)	(0.09,0.16,0.22)	(0.21,0.45,0.64)	(0.00,0.01,0.01)	(0.00,0.01,0.01)	(0.00,0.00,0.00)	(0.04,0.11,0.23)
	17	(0.02,0.04,0.06)	(0.00,0.00,0.00)	(0.01,0.01,0.02)	(0.02,0.04,0.06)	(0.00,0.00,0.00)	(0.00,0.01,0.01)	(0.00,0.00,0.00)	(0.00,0.01,0.02)

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respondent had been engaged in a different profession. The age distribution of the respondents ranged from 20 to 60 years, with a majority (84%) falling between 30 and 49 years. A large number of the respondents (72%) had various experiences in hazard management. In addition, most of the respondents (92%) have acquired postgraduate degrees. The specific information from the interviewees is shown in Fig. 3.

Respondents were only required to mark the line adjacent to one of the labels (Definitely required, Required, Not related), and they could suggest other opinions and items in relation to the criteria. Then, indicators were adopted if the mean and median were over "Requited" grade. Further, one indicator, i.e., annual maximum flood damage during 1971-2006, was added based on the proposal of some experts. In the end, 16 indicators were adopted for spatial flood risk vulnerability assessment. All these indicators were divided into a hierarchical step, themes (objectives), as shown in Table 1.

From two-round survey, all criteria were determined. Six criteria for social risks were selected: (1) population growth ratio, (2) population, (3) metropolitan area, (4) annual average flood victims, (5) annual average flood casualties and (6) local government competence. Five criteria for economic risks were selected (1) establishments, (2) labor force participation rate, (3) average cost of land, (4) annual average flood damage and (5) annual maximum flood damage during 1971-2006. Five hydrologic criteria were selected: (1) maximum inundation area, (2) 200-yr frequency flood, (3) maximum flood flow (2005-2010), (4) 200-year flood inundation area using GIS software, and (5) flood defense facilities.

4.2. Weights estimation

This process was divided into two parts. Firstly the respondents subjectively determined the weights. Then, they received the previous results as feedback and reevaluated the weights based on it. The collected weights based on the hierarchy were as follows: (1) themes (objectives)-social, economic, and hydrologic risk and (2) 16 individual indicators.

The weights of the three themes (W_{sn}; n = 1, 2, 3) and each indicator (W_{in}; n = 1, ..., 16) were determined based on the survey results. A tree structure was used to obtain the final weights (W_n; n = 1, ..., 16). The final weights for the indicator at each twig of the tree were obtained by multiplying through the branches. To follow this procedure, we combined the weights of the indicators and the three themes. As the results, the most important theme is hydrologic risk. It is weighted at W_{s3} (0.74, 0.93, 0.95). Among the indicators, the annual number of floods and flood inundation areas show high level weighting values using the collected weights. In addition, the combined weights also provided the same results.

4.3. Step 3. Data acquisition and fuzzification

All data of 17 sub-regions are collected from administrative materials such as governmental agencies, National statistical office and National emergency management agency, etc. Collected data of divided areas were fuzzified using TFN concept (Eq. (1)) as shown in Table 2. Each TFN was derived from the probability density function (PDF) using R-statistics software shown in Fig. 4. We

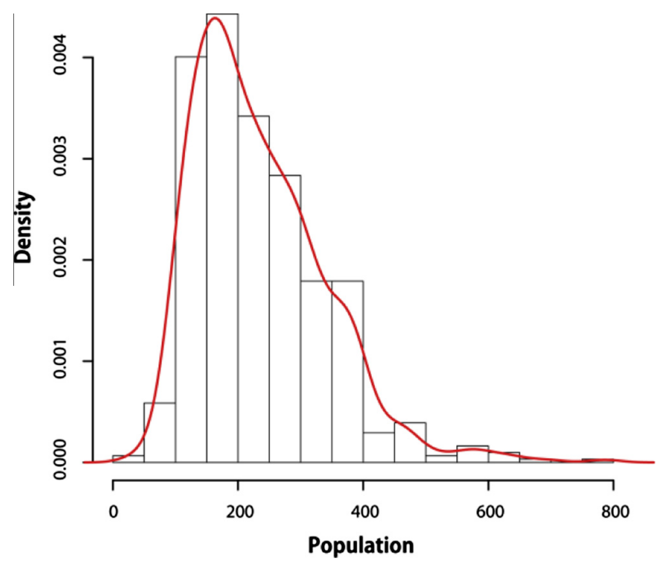
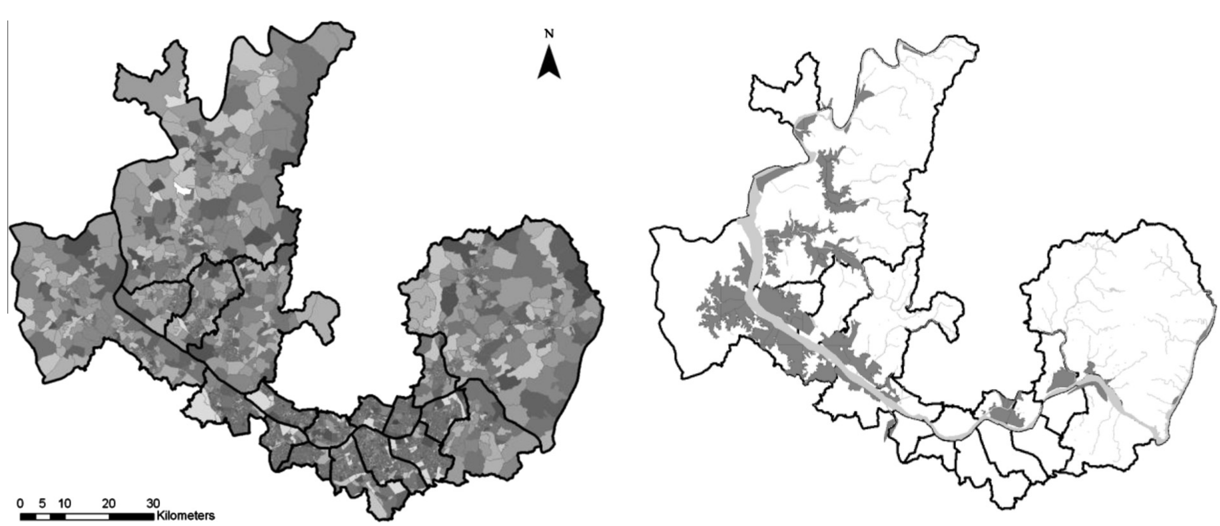


Fig. 4. Examples of FTNs (left 03).



(a) Population (b) Flood inundation areas

Fig. 5. Examples of evaluation database for the study area.

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Table 3
α-Level sets of the fuzzy relative closenesses of the 17 sub-regions.

α	Alternative (left bank unit: 01–08, Right bank unit: 09-17)								
	01	02	03	04	05	06	07	08	
0.0	[0.26,0.84]	[0.24,0.78]	[0.33,0.69]	[0.23,0.82]	[0.24,0.74]	[0.14,0.55]	[0.06,0.23]	[0.25,0.59]	
0.1	[0.30,0.84]	[0.28,0.79]	[0.39,0.70]	[0.28,0.84]	[0.28,0.76]	[0.16,0.53]	[0.07,0.23]	[0.28,0.58]	
0.2	[0.34,0.85]	[0.32,0.79]	[0.45,0.72]	[0.33,0.86]	[0.33,0.78]	[0.18,0.52]	[0.08,0.22]	[0.30,0.57]	
0.3	[0.39,0.84]	[0.36,0.79]	[0.51,0.73]	[0.38,0.88]	[0.38,0.80]	[0.21,0.51]	[0.09,0.21]	[0.33,0.57]	
0.4	[0.43,0.84]	[0.40,0.78]	[0.57,0.75]	[0.43,0.89]	[0.44,0.82]	[0.23,0.50]	[0.10,0.21]	[0.35,0.56]	
0.5	[0.48,0.83]	[0.44,0.77]	[0.64,0.77]	[0.49,0.90]	[0.49,0.84]	[0.26,0.48]	[0.11,0.20]	[0.38,0.55]	
0.6	[0.53,0.81]	[0.49,0.76]	[0.70,0.79]	[0.54,0.89]	[0.55,0.86]	[0.29,0.47]	[0.12,0.20]	[0.41,0.54]	
0.7	[0.58,0.79]	[0.53,0.74]	[0.75,0.81]	[0.60,0.86]	[0.61,0.86]	[0.32,0.46]	[0.13,0.19]	[0.43,0.53]	
0.8	[0.63,0.77]	[0.58,0.72]	[0.80,0.83]	[0.66,0.83]	[0.67,0.85]	[0.36,0.45]	[0.14,0.19]	[0.46,0.52]	
0.9	[0.67,0.74]	[0.63,0.69]	[0.83,0.85]	[0.71,0.80]	[0.73,0.82]	[0.39,0.44]	[0.16,0.18]	[0.48,0.52]	
1.0	[0.72,0.72]	[0.67,0.67]	[0.86,0.86]	[0.76,0.76]	[0.78,0.78]	[0.42,0.42]	[0.17,0.17]	[0.51,0.51]	
	Alternative								
	09	10	11	12	13	14	15	16	17
0.0	[0.33,0.59]	[0.30,0.69]	[0.24,0.67]	[0.27,0.80]	[0.31,0.80]	[0.26,0.83]	[0.16,0.65]	[0.22,0.92]	[0.16,0.50]
0.1	[0.38,0.60]	[0.35,0.70]	[0.28,0.68]	[0.31,0.82]	[0.36,0.82]	[0.31,0.85]	[0.19,0.63]	[0.26,0.90]	[0.17,0.48]
0.2	[0.42,0.61]	[0.40,0.72]	[0.33,0.69]	[0.36,0.84]	[0.41,0.84]	[0.36,0.88]	[0.22,0.62]	[0.30,0.87]	[0.19,0.47]
0.3	[0.47,0.61]	[0.45,0.73]	[0.38,0.70]	[0.41,0.86]	[0.47,0.86]	[0.41,0.90]	[0.25,0.60]	[0.34,0.85]	[0.21,0.46]
0.4	[0.51,0.62]	[0.51,0.75]	[0.43,0.70]	[0.47,0.87]	[0.52,0.88]	[0.46,0.93]	[0.28,0.59]	[0.39,0.82]	[0.23,0.44]
0.5	[0.55,0.63]	[0.56,0.76]	[0.48,0.71]	[0.52,0.88]	[0.58,0.91]	[0.52,0.94]	[0.31,0.57]	[0.43,0.80]	[0.26,0.43]
0.6	[0.59,0.64]	[0.62,0.77]	[0.53,0.71]	[0.57,0.88]	[0.64,0.93]	[0.57,0.93]	[0.34,0.55]	[0.48,0.77]	[0.28,0.42]
0.7	[0.62,0.65]	[0.67,0.79]	[0.58,0.71]	[0.63,0.87]	[0.70,0.94]	[0.63,0.90]	[0.38,0.54]	[0.53,0.75]	[0.30,0.41]
0.8	[0.64,0.66]	[0.71,0.79]	[0.62,0.71]	[0.68,0.84]	[0.76,0.92]	[0.69,0.87]	[0.42,0.52]	[0.58,0.72]	[0.33,0.40]
0.9	[0.66,0.67]	[0.75,0.79]	[0.65,0.70]	[0.74,0.82]	[0.81,0.89]	[0.74,0.83]	[0.46,0.51]	[0.63,0.70]	[0.35,0.39]
1.0	[0.68,0.68]	[0.79,0.79]	[0.68,0.68]	[0.78,0.78]	[0.86,0.86]	[0.79,0.79]	[0.49,0.49]	[0.67,0.67]	[0.38,0.38]

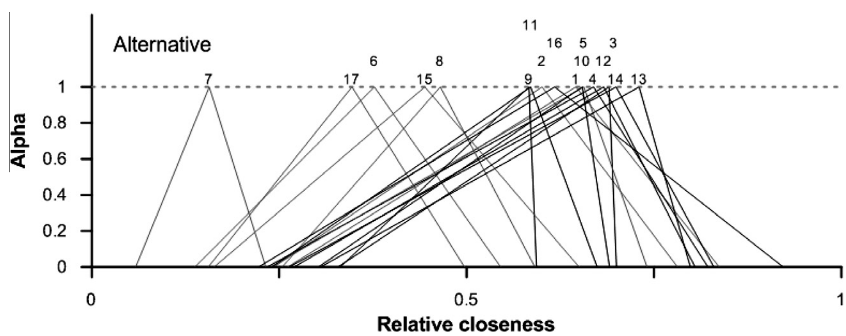

Fig. 6. The fuzzy relative closeness of 17 sub-regions.

assumed that if a province has a value, or very little variability, one value is used. The collected data is spatially analyzed using GIS tools as shown Fig. 5.

4.4. Fuzzy TOPSIS application

Using eleven α levels, fuzzy TOPSIS was applied to the normalized fuzzy decision matrix. The relative closenesses from positive and negative ideal points are calculated using Eqs. (12) and (13) as shown in Table 3. Using those relative closenesses according to eleven α levels and the defuzzfication method, Eqs. (14) and (15), all fuzzy relative closenesses are calculated as shown in Fig. 6. As a result, A11 is the most vulnerable and A7 the opposite. Some are symmetric while A3, A12, A13, and A14 are leaned to the right side.

4.5. Comparison of fuzzy TOPSIS and α-level based fuzzy TOPSIS

This study compared two results between from fuzzy TOPSIS and α-level based fuzzy TOPSIS and the results are shown in Table 4 and Figs. 7 and 8. Table 4 showed the calculated defuzzfied values of fuzzy TOPSIS and relative closeness of α-level based fuzzy TOPSIS. Figs. 7 and 8 showed the normalized assessing values of two methods and their rankings of left and right bank sides, respectively. It seems to be small since the spearman rank coefficients are 0.98 for left-side, 0.82 for right-side and 0.89 for both. Some differences, however, can be significant such as A9 and A14. A9 and A14 showed dramatic changes after the application of α-level based fuzzy TOPSIS. The ranking of A3 and A13 varied from 1st to 3rd and from 3rd to 1st, respectively. It can be easily guessed that the value interval affect the ranking of α-level based fuzzy TOPSIS.

If the original distributions of 17 sub-regions to hydrologic, social, and economic criteria are derived, the results are shown in Fig. 9.The value intervals are all different, e.g., A7 has narrow interval while A9 and A13 have large value variations.

The TFNs of evaluation material which described in Fig. 6 contribute to the reason of this change. There is no critical evaluation difference between left and right banks. In the floodplain area of right bank, vulnerability ranking changed dynamically. Particularly, there are great differences of A12 and A14 which showed positive status from fuzzy TOPSIS but negative rankings from α-level based fuzzy TOPSIS. On the other hand, A9, A10 and A11 showed the opposite rankings.

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When examine relative closeness, the vertex of fuzzy number lean to one side as appeared in alternative which have great ranking change like this. While for the case of alternative of left bank that have similar with case which did not apply α-level, fuzzy number generally appear regular triangle and the difference between mean-lower and upper-mean is small. In other words, in evaluation α-level scheme reflect these material and fuzzy number shape of weights according to change the value of a between 0 and 1. So could reflect evaluation material and weights more properly comparing with the method using lower, mean, and upper.

That is, A2, A7, A17, A6, and A8 which showed no ranking change or small have their centro-symmetric distributions in Fig. 6, while A3, A4, A9, A11, A12, A13 and A14 whose rankings varied dynamically, have biased (anti-symmetric) distributions. Therefore, α-level based fuzzy TOPSIS can consider the uncertainty of defuzzification process inherent in fuzzy MCDM method.

For the clear representation, the results can be reorganized as shown in Fig. 8 according to what side they are adjacent to. It can be concluded that the downstream region adjacent to the right bank should be large variations between two fuzzy TOPSIS methods and the upstream region showed much more vulnerable condition on both sides.

In addition, Fig. 10 for the graphical representation was added. It can be the general flood vulnerability map which help decision makers know the potential flood hazard at a glance.

Table 4
Evaluating results using α-cut fuzzy TOPSIS and fuzzy TOPSIS methods.

	Alternative	α-Cut fuzzy TOPSIS		Fuzzy TOPSIS	
		Defuzzified Value	Rank	Relative closeness	Rank
Left bank	A1	0.6316	10	0.1762	10
	A2	0.5712	11	0.1341	12
	A3	0.7030	4	0.3664	1
	A4	0.7134	3	0.2891	4
	A5	0.6747	7	0.2535	6
	A6	0.4208	14	0.0634	14
	A7	0.4196	15	0.0504	15
	A8	0.2431	17	0.0081	17
Right bank	A9	0.5546	12	0.2510	8
	A10	0.6500	8	0.2672	5
	A11	0.6894	5	0.3587	2
	A12	0.6893	6	0.2393	9
	A13	0.7416	1	0.3046	3
	A14	0.7142	2	0.2529	7
	A15	0.4735	13	0.0891	13
	A16	0.6385	9	0.1755	11
	A17	0.2505	16	0.0133	16

5. Conclusions

α-cut level set fuzzy TOPSIS scheme suggested by Wang and Elhag (2006) is known as a method that has the effect of reducing uncertainty inherent in fuzzy MCDM process. This study applied this method to the real flood vulnerability quantification problem in Han River reach flowing through Seoul where it is the capital of Korea and significant region of economic, social and cultural views while Wang and Elhag (2006) applied it to the very simple examples. In addition this study compared the result from general fuzzy TOPSIS.

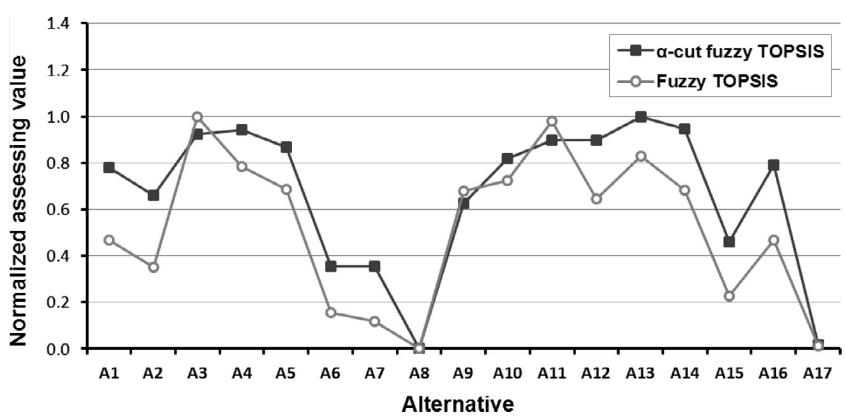

Fig. 7. Comparison of normalized vulnerability evaluation values from fuzzy TOPSIS and α-level based fuzzy TOPSIS.

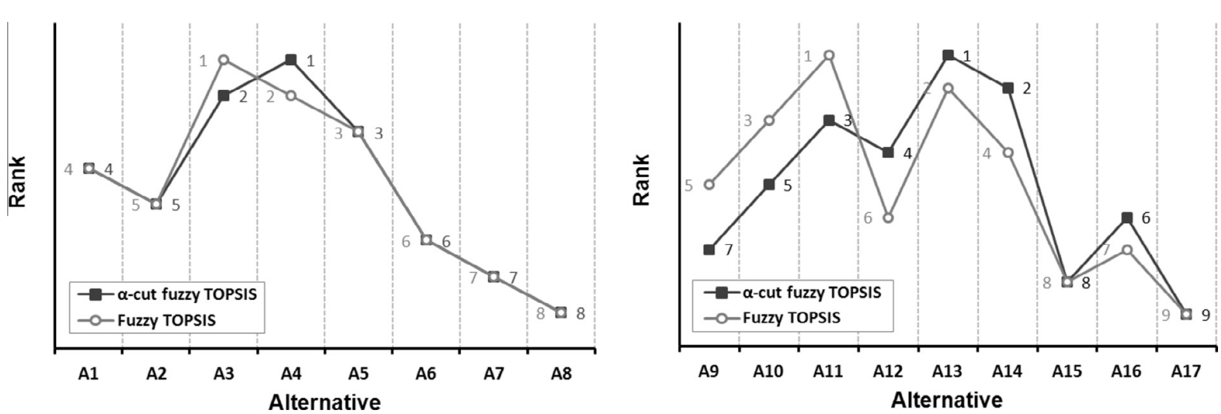

Fig. 8. Ranking comparisons of left-side and right-side banks from fuzzy TOPSIS and α-level based fuzzy TOPSIS.

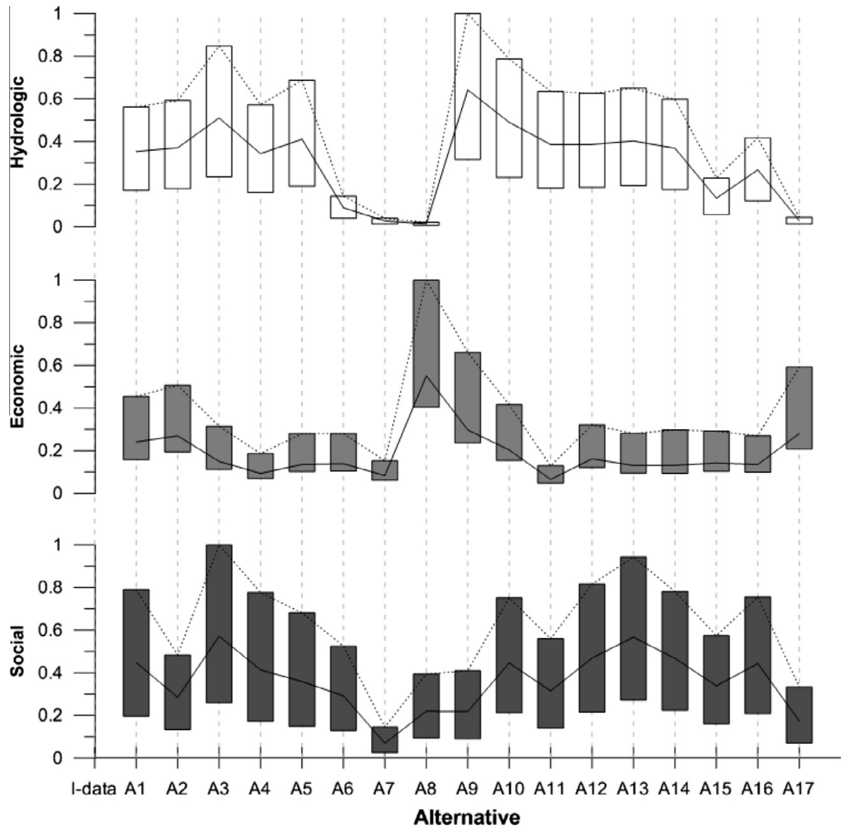

Fig. 9. Distributions of each sub-section.

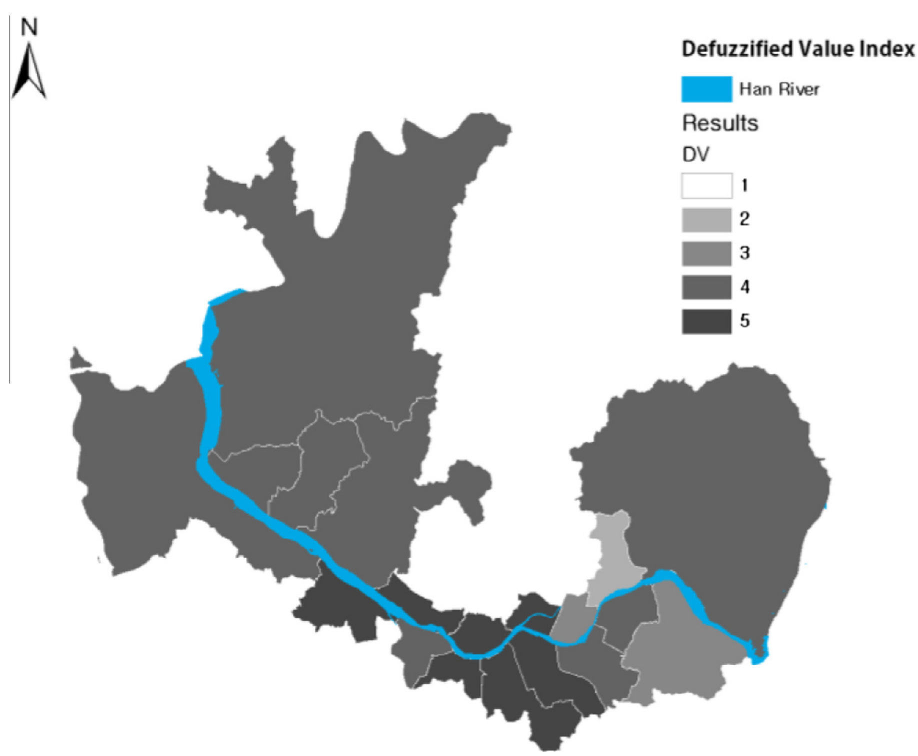

Fig. 10. Results using α-level based fuzzy TOPSIS.

As a result of estimation using α-cut level sets, there are some ranking differences. It seems to be small since the spearman rank coefficients are 0.98 for left-side, 0.82 for right-side and 0.89 for both. Some differences, however, can be significant such as A9 and A14. A9 and A14 showed dramatic changes after the application of α-cut level sets based fuzzy TOPSIS. The ranking of A3 and A13 varied from 1st to 3rd and from 3rd to 1st, respectively. It can be easily guessed that the value interval affect the ranking of α-cut level sets based fuzzy TOPSIS. That is, the totally-different results came out in some sub-regions since the advantage of collecting fuzzy data becomes unapparent if general fuzzy MCDM problem is defuzzified into a crisp one at the very beginning. That is, α-level fuzzy TOPSIS scheme defuzzify imprecise values at the end of the process, not from the very beginning. Also, this study developed very useful representations such as administrative flood vulnerability approach adjacent to each bank and spatial flood vulnerability map. They can help decision makers know the potential flood hazard at a glance.

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References

Afshar, A., Mariño, M. A., Saadatpour, M., & Afsahr, A. (2011). Fuzzy TOPSIS multi-criteria decision analysis applied to Karun reservoirs system. *Water Resource Management, 25*, 545–563.

Akter, T., & Simonovic, S. P. (2005). Aggregation of fuzzy views of a large number of stakeholders for multi-objective flood management decision-making. *Journal of Environment Management, 77*, 133–143.

Balica, S. F., Popescu, I., Beevers, L., & Wright, N. G. (2013). Parametric and physically based modelling techniques for flood risk and vulnerability assessment: A comparison. *Environmental Modelling & Software, 41*, 84–92.

Chen, C. T. (2000). Extension of the TOPSIS for group decision-making under fuzzy environment. *Fuzzy Sets and Systems, 114*, 109.

Chu, T. C. (2002). Selecting plant location via a fuzzy TOPSIS approach. *International Journal of Advanced Manufacturing Technology, 20*, 859–864.

Chung, E. S., & Lee, K. S. (2009). Identification of spatial ranking of hydrological vulnerability usingmulticriteria decision making techniques: Case study of Korea. *Water Resource Management, 23*, 2395–2416.

Chung, E. S., Hong, W. P., Lee, K. S., & Burian, S. J. (2011). Integrated use of a continuous simulation model and multi-attribute decision amking for ranking urban watershed management alternatives. *Water Resource Management, 25*, 641–659.

Frerks, G., Bankoff, G., & Hilhorst, D. (2004). *Mapping vulnerability: disasters, development and people*. London: Earthscan.

Fu, G. (2008). A fuzzy optimization method for multi-criteria decision making: An application to reservoir flood control operation. *Expert System with Applications, 34*, 145–149.

Hamouda, M. A., Nour El-Din, M. M., & Moursy, F. I. (2009). Vulnerability assessment of water resources systems in the Eastern Nile Basin. *Water Resources Management, 23*, 2697–2725.

Hwang, C. L., & Yoon, K. (1981). *Multiple attributes decision-making methods and applications*. Heidelberg: Springer.

IPCC (2001). Climate Change 2001: impacts, adaptation vulnerability. Contribution of working group II to the third assessment report of the intergovernmental panel on climate change. Geneva: UNEP/WMO.

Jun, K. S., Chung, E. S., Kim, J. Y., & Lee, K. S. (2011). Development of spatial water resources vulnerability index considering climate change impacts. *Science of the Total Environment, 409*, 5228–5242.

Jun, K. S., Chung, E. S., Kim, Y. G., & Kim, Y. (2012). A fuzzy multi-criteria approach to flood risk vulnerability in South Korea by considering climate change impacts. *Expert Systems with Applications, 40*, 1003–1013.

Kang, B. S., Lee, J. H., Chung, E. S., Kim, D. S., & Kim, Y. D. (2013). A sensitivity analysis approach of multi-attribute decision making technique to rank flood mitigation projects. *KSCE Journal of Civil Engineering, 17*(6), 1529–1539.

Kaufmann, A., & Gupta, M. M. (1991). *Introduction to Fuzzy Arithmetic: Theory and Application*. New York: Van Nostrand Reinhold.

Kim, G., Park, C. S., & Yoon, K. P. (1997). Identifying investment opportunities for advanced manufacturing systems with comparative-integrated performance measurement. *International Journal of Production Economics, 50*, 23–33.

Kim, Y., & Chung, E. S. (2013). Fuzzy VIKOR approach for assessing the vulnerability of the water supply to climate change and variability in South Korea. Applied Mathematical Modelling, http://dx.doi.org/10.1016/j.apm.2013.04.040.

Knight, F. H. (1921). *Risk, Uncertainty, and Profit*. Library of Economics and Liberty. Retrieved March 26, 2013 from the World Wide Web: http://www.econlib.org/library/Knight/knRUP1.html.

Lai, Y. J., Liu, T. Y., & Hwang, C. L. (1994). TOPSIS for MODM. *European Journal of Operational Research, 76*, 486–500.

Lee, G. M., Jun, K. S., & Chung, E. S. (2013). Integrated multi-criteria flood vulnerability approach using Fuzzy TOPSIS and Delphi technique. *Natural Hazards and Earth System Sciences, 13*, 1293–1312.

Linstone, H. A., & Turoff, M. (1975). *The Delphi method: techniques and application*. Addison-Wesley Publishing Company Advanced Book Program.

Meyer, V., Scheuer, S., & Haase, D. (2009). A multictiteria approach for flood risk mapping exemplified at the Mulderiver, Germany. *Natural Hazards, 48*, 17–39.

Moel, H., Alphen, J., & Aerts, J. (2009). Flood maps in Europe - methods, availability and use. *Nat Hazards and Earth System Sciences, 9*, 289–301.

Risk and Policy Analysts (RPA) Ltd. (2004). Evaluating a multi-criteria analysis methodology for application to flood management and coastal defence appraisals. R&D Technical Report, DEFRA.

Sayers, P., Hall, J., Dawson, R., Rosu, C., Chatterton, J., & Deakin, R. (2011). *Risk assessment of flood and coastal defenses for strategic planning (rasp)-A high level methodology*. Wallingford.

Seager, J. (2001). Perspectives and limitations of indicators in water management. *Regional Environmental Change, 2*(2), 85–92.

Sebald, C. (2010). Towards an integrated flood vulnerability index: A flood vulnerability assessment. Master of Science (MSc).

Shih, H. S., Shyur, H. J., & Lee, E. S. (2007). An extension of TOPSIS for group decision making. *Mathematical and Computer Modelling, 45*, 801–813.

Simonovic, S. P., & Niruoama (2005). A spatial multi-objective decision-making under uncertainty for water resources management. *Journal of Hydroinformatics, 7*, 117–133.

Smith, K. (2004). *Environmental Hazards: Assessing Risk and Reducing Disaster*. London: Routledge.

Thinh, N. X., & Vogel, R. (2006). *GIS-based multiple criteria analysis for land-use suitability assessment in the context of flood risk management*. Berlin: InterCarto - InterGIS 12.

Torlak, G., Sevkli, M., Sanal, M., & Zaim, S. (2011). Analyzing business competition by using fuzzy TOPSIS method: An example of Turkish domestic airline industry. *Expert Systems with Applications, 38*, 3396–3406.

Triantaphyllou, E., & Lin, C. T. (1996). Development and evaluation of five fuzzy multiattribute decision-making methods. *International Journal of Approximate Reasoning, 14*, 281–310.

Tsaur, S. H., Chang, T. Y., & Yen, C. H. (2002). The evaluation of airline service quality by fuzzy MCDM. *Tourism Management, 23*, 107–115.

Wang, Y. M., & Elhag, T. M. S. (2006). Fuzzy TOPSIS method based on alpha level sets with an application to bridge risk assessment. *Expert Systems with Applications, 31*, 309–319.

Zhou, H. C., Wang, G. L., & Yang, Q. (1999). A multi-objective fuzzy pattern recognition model for assessing groundwater vulnerability based on the DRASTIC system. *Hydrological Sciences, 44*, 611–618.