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ORIGINAL PAPER

Evaluation of basin environmental vulnerability: the weighted method compared to the compromise method

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Abstract Environmental vulnerability analysis is an important issue in conducting sustainable basin management. In our past study, we developed a set of criteria from three categories of factors (geographic, hydrologic, and societal) for assessing basin environmental vulnerability. According to a survey and the analytical hierarchy process (AHP) analysis, seven criteria were selected as a set of criteria, and the weights of these criteria were determined. This study adopts two different multiple criteria analysis (MCA) methods, the weighted method and the compromise method, to integrate the criteria and evaluate the environmental vulnerability of major basins in Taiwan. The results show that the Cho-Shui River Basin has the highest environmental vulnerability, no matter which method is used. However, the environmental vulnerability of the Ta-Chia River Basin is higher than that of the Tan-Shui River Basin and the Tseng-Wen River Basin when considering the measure of individual regret by the modified VIKOR method, which generates a different ranking than that of the weighted method. Stricter land-use restrictions should be placed on those basins that have higher environmental vulnerability. According to the analysis, the results of basin environmental vulnerability, land-use classification strategies can be created.

Keywords Basin · Environmental vulnerability · Multiple criteria analysis · The compromise method · The weighted method

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Introduction

As a result of climate change, numerous natural disasters frequently occur around the world. Water-related environmental problems, such as extreme storms, floods, droughts, or debris flow, have become a greater challenge in the twenty-first century. Basin management is a critical issue in sustainable water resource protection and management. Owing to scanty land resources in Taiwan, land-use classification instead of conventional structural protection strategies has been popularly applied in basin management (Lin et al. 2000, 2001; Wang 2001; Chang and Hsu 2009). Environmental vulnerability analysis can be an important reference for creating land-use management strategies (Villa and McLeod 2002; Chang et al. 2008a; Chang and Hsu 2011).

Multiple influencing factors should be considered in environmental vulnerability analysis (US Environmental Protection Agency 1991; Briguglio 1995; Pantin 1997; Kaly and Pratt 2000; Committee to Assess the Scientific Basis of the TMDL Approach to Water Pollution 2001; Villa and McLeod 2002). Multiple criteria analysis (MCA) can be a useful method in integrating criteria with different degrees of influence (Opricovic 1998; Opricovic and Tzeng 2004; Tzeng et al 2005). There are several methods for solving MCA problems. The weighted method, the compromise method, and the constraint method have been commonly applied in MCA (Opricovic and Tzeng 2007; Ahn and Park 2008; Chang 2010). In our past study, we determined a set of criteria and criteria weights from a survey and the analytical hierarchy process (AHP) analysis (Chang and Chao 2011). This study uses two different methods, the weighted method and the compromise method, to integrate the criteria and compares the environmental vulnerability of five main basins in Taiwan.

Because these methods have different calculation properties, the ranking of environmental vulnerability of these basins may also change.

Materials and methods

Environmental vulnerability analysis

Most studies have stated that environmental vulnerability is related to diverse factors. These factors can be considered as part of three categories: geographic, hydrologic, and societal (Downs et al. 1991; Mostaghimi et al. 1997; Kaly et al. 1999, 2002; Jaspers 2003; Chang et al. 2008b; Chang and Hsu 2009, 2011). In our past study, we developed a set of criteria for describing basin environmental vulnerability. These criteria were as follows: vegetation cover condition, landslide area size, soil type, average annual precipitation, average duration of extreme storms, land-use type, and population density. The effects of these criteria on basin environmental vulnerability are different. The criteria weights, which were determined by a survey and the AHP method, can describe the degree of impact of each criterion (Saaty 1980, 1990, 2008; Noble and Sanchez 1993). The weights of these seven criteria were 0.13, 0.28, 0.14, 0.11, 0.12, 0.14, and 0.08, respectively (Chang and Chao 2011). The criterion "landslide area size" has the greatest influence on basin environmental vulnerability. Having different units, these criteria should be transformed to dimensionless indicators on a single scale (Craig and Karen 1995). Table 1 lists these criteria, their weights, and their classified four grades (1, 4, 7, and 10). The total score of each basin is determined by MCA. Various MCA methods can generate different rankings of basin environmental vulnerability. This study discusses two MCA methods, the weighted method and the compromise method, and introduces these methods below.

Description of basin environment

This study considers Taiwan's five main basins for environmental vulnerability. These basins are: the Tan-Shui River Basin, the Ta-Chia River Basin, the Cho-Shui River Basin, the Tseng-Wen River Basin, and the Kao-Ping River Basin. Figure 1 shows the relative location of these basins in Taiwan. The Tan-Shui River Basin is located in northern Taiwan. The length of the Tan-Shui mainstream is 159 km. The Tan-Shui River Basin covers 2,726 km^2. The Ta-Chia River Basin and the Cho-Shui River Basin are located in central Taiwan. Their mainstream lengths are 124 and 186 km, respectively. They cover 1,236 and 3,157 km^2, respectively. The Tseng-wen River Basin and the Kao-Ping River Basin are located in southern Taiwan. Their mainstream lengths are 138 and 171 km, respectively. They cover 1,176 and 3,257 km^2, respectively. Table 2 summarizes the environmental properties of these five main basins. According to the original information of these basins, the classified score of each criterion can be determined.

Multiple criteria analysis (MCA) methods

The weighted method

The weighted method is a very common method for solving MCA problems (Guh 1997; Ahn and Park 2008). The five basins are denoted as x_1, x_2,…, and x_5. f_{ij} is the value of the i^{th} criterion function for the basin x_j. w_i is the weight of the i^{th} criteria. The total score of each basin is calculated by the weight and the score of each criterion in this method. The calculation of the weighted method is as follows:

$$B_j = w_i \times f_{ij} \tag{1}$$

where B_j is the total score of basin x_j. When the basin has larger B_j, it indicates that the environmental vulnerability is

Table 1 Weights and classified scores of criteria

Criterion	Weight	Score			
		1	4	7	10
Vegetation cover condition	0.13	Excellent	Good	Fair	Bad
Landslide area size (ha)	0.28	<1,000	1,000–5,000	5,000–10,000	>10,000
Soil type	0.14	Gravel	Sand	Clay	Silt
Average annual precipitation (mm)	0.11	<2,600	2,600–2,900	2,900–3,100	>3,100
Average duration of extreme storms (days)	0.12	<17	17–18	19–20	>20
Land-use type	0.14	Forest	Farmland	Park	Urbanized area
Population density (people/km^2)	0.08	<400	400–700	700–1,000	>1,000

Chang and Chao 2011

Fig. 1 The five main basins in Taiwan

higher in that basin. That is, the larger the total score, the greater the environmental vulnerability of that basin. Basins having higher environmental vulnerability should implement more serious land-use restrictions.

The compromise method

When the criteria conflict in MCA, the solution cannot satisfy all criteria. In these situations, the compromise method based on the concept of Pareto optimality is usually adopted (Pareto 1896; Kuhn and Tucker 1951; Zadeh 1963; Opricovic 1998; Tzeng et al. 2002; Opricovic and Tzeng 2004, 2007; Tong et al. 2007). This study applies the modified VIKOR method as the compromise method. The algorithm of the modified VIKOR method is listed in the following steps.

- Determine the alternatives and criteria. The various alternatives are denoted as x_1, x_2,..., x_m. m is the number of alternatives. f_{ij} is the value of the i^{th} criterion function for the alternative x_j. n is the number of criteria. In this study, basins can be regarded as alternatives; m is 5; and n is 7. This step is the same as that of the weighted method.
- Determine the maximum f_i^* and the minimum f_i^- values of all criterion functions, $i = 1\ldots n$.

$$f_i^* = j\max f_{ij} = \max[(f_{ij})|j = 1, 2, \ldots\ldots, m] \quad (2)$$

$$f_i^- = j\min f_{ij} = \min[(f_{ij})|j = 1, 2, \ldots\ldots, m] \quad (3)$$

- Compute the values S_j and R_j, $j = 1\ldots\ldots m$.

$$S_j = \sum_{i=1}^{n} w_i\left(f_i^* - f_{ij}\right)/\left(f_i^* - f_i^-\right) \quad (4)$$

$$R_j = i\max[w_i(f_i^* - f_{ij})/(f_i^* - f_i^-)|i = 1, 2, \ldots\ldots, n] \quad (5)$$

where S_j and R_j represent the utility measure and the regret measure for the alternative x_j, respectively. w_i are

Table 2 Environmental properties of the five main basins in Taiwan

Criteria	Original information of these basins					Classified score of these basins				
	Tan-Shui River Basin	Ta-Chia River Basin	Cho-Shui River Basin	Tseng-wen River Basin	Kao-Ping River Basin	Tan-Shui River Basin	Ta-Chia River Basin	Cho-Shui River Basin	Tseng-wen River Basin	Kao-Ping River Basin
Vegetation cover condition	Good	Good	Good	Good	Good	4	4	4	4	4
Landslide area size (ha)	313	4,178	11,279	625	3,413	1	4	10	1	4
Soil type	Sand	Sand	Sand	Sand	Sand	4	4	4	4	4
Average annual precipitation (mm)	3,172	2,376	2,353	3,005	3,139	10	1	1	7	10
Average duration of extreme storms (days)	15	17	20	21	22	1	4	7	10	10
Land-use type	Forest	Forest	Forest	Forest	Forest	1	1	1	1	1
Population density (people/km^2)	1,769	305	374	624	384	10	1	1	4	1

Chang and Chao 2011

the weights of the i^{th} criteria. The larger the value of S_j, the less the group utility; the larger the value of R_j, the larger the individual regret. We can also use the index $1 - S_j$ to represent the measure of group utility. The larger the value of $1 - S_j$, the larger the group utility is.

- Calculate the modified VIKOR index Q_j^*, $j = 1\ldots\ldots m$.

$$Q_j^* = \begin{cases} v(S_j - S^*)/(S^- - S^*) + (1-v)(R_j - R^*)/(R^- - R^*) & S^- \neq S^* \cap R^- \neq R^* \\ (R_j - R^*)/(R^- - R^*) & S^- = S^* \cap R^- \neq R^* \\ (S_j - S^*)/(S^- - S^*) & R^- = R^* \cap S^- \neq S \\ k = \text{constant} & S^- = S^* \cap R^- = R^* \end{cases} \quad (6)$$

$$S^* = j\min S_j = \min[(S_j)|j = 1, 2, \ldots\ldots, m] \quad (7)$$

$$S^- = j\max S_j = \max[(S_j)|j = 1, 2, \ldots\ldots, m] \quad (8)$$

$$R^* = j\min R_j = \min[(R_j)|j = 1, 2, \ldots\ldots, m] \quad (9)$$

$$R^- = j\max R_j = \max[(R_j)|j = 1, 2, \ldots\ldots, m] \quad (10)$$

where v is the weight for the strategy of maximum group utility; $1 - v$ is the weight of the individual regret (Kackar 1985; Opricovic 1998). When v is 0.5, it indicates that the measure of the group utility and the measure of the individual regret have equal influence for determining the ranking of alternatives. When v is 1, the ranking of alternatives is only determined by the measure of the group utility; when v is 0, the ranking of alternatives is only determined by the measure of the individual regret.

- Rank the alternatives by the modified VIKOR index Q_j^*. The basins that have lower values of Q_j^* have higher environmental vulnerability, and should implement more severe land-use restraint restrictions.

Results and discussion

Table 3 shows the ranking of the environmental vulnerability of the five basins discussed in this study. The results show that the Cho-Shui River Basin has the highest environmental vulnerability, no matter which method is used. Because the criterion "landslide area size" is the most important factor in basin environmental vulnerability analysis, and the landslide area is the largest in the Cho-Shui River Basin, the results make sense. The average annual precipitation is 3,139 mm, and the average duration of extreme storms is 22 days in the Kao-Ping River Basin. The rainfall characteristics in the Kao-Ping River Basin cause soil erosion to be much more likely. The Kao-Ping River Basin has the second highest environmental vulnerability among these basins, no matter which method is used. However, the ranking of basin environmental vulnerability for the Tan-Shui River Basin, the Ta-Chia River Basin, and the Tseng-Wen River Basin are different when using the weighted method and the compromise method (the modified VIKOR method).

The modified VIKOR method can consider both the influence of group utility and the influence of individual regret among the basins. Figure 2 shows the measure of group utility, $1 - S_j$, and the measure of individual regret, R_j, for the five basins. The landslide area in the Ta-Chia River Basin is about 4,178 km^2. The landslide areas in the Tan-Shui River Basin and the Tseng-Wen River Basin are about 313 and 625 km^2, respectively. The size of landslide area in the Ta-Chia River Basin is much larger than that of the Tan-Shui River Basin and the Tseng-Wen River Basin. The small size of landslide area can be regarded as an individual regret of the Tan-Shui River Basin and the Tseng-Wen River Basin. Although the group utility of the Ta-Chia River Basin is the least among these basins, its individual regret is less than that of the Tan-Shui River Basin and the Tseng-Wen River Basin. Therefore, the environmental vulnerability of the Ta-Chia River Basin is higher than that of the Tan-Shui River Basin and the Tseng-Wen River Basin according to the analysis results of basin environmental vulnerability, when using the modified VIKOR method as $v = 0.5$ or $v = 0$. In other words, the Ta-Chia River Basin should implement more serious land-use restrictions than the Tan-Shui River Basin and the Tseng-Wen River Basin, when considering the measure of individual regret of the other basins.

The modified VIKOR method only considers the group utility as $v = 1$. The ranking of basin environmental vulnerability using the weighted method provides the same results as using the modified VIKOR method with $v = 1$. The results indicate that the weighted method respects the measure of group utility rather than the measure of

Table 3 The ranking of basin environmental vulnerability

Index and rank	Basins				
	Tan-Shui River Basin	Ta-Chia River Basin	Cho-Shui River Basin	Tseng-wen River Basin	Kao-Ping River Basin
B_{j}	3.52	3.01	5.05	3.79	4.72
The ranking of basin environmental vulnerability by the weighted method	4	5	1	3	2
Q_j^* (as $v = 0.5$)	0.88	0.73	0.00	0.81	0.31
The ranking of basin environmental vulnerability by the modified VIKOR method (as $v = 0.5$)	5	3	1	4	2
Q_j^* (as $v = 1$)	0.8	1.0	0.0	0.6	0.2
The ranking of basin environmental vulnerability by the modified VIKOR method (as $v = 1$)	4	5	1	3	2
Q_j^* (as $v = 0$)	1.00	0.45	0.00	1.00	0.45
The ranking of basin environmental vulnerability by the modified VIKOR method (as $v = 0$)	3	2	1	3	2

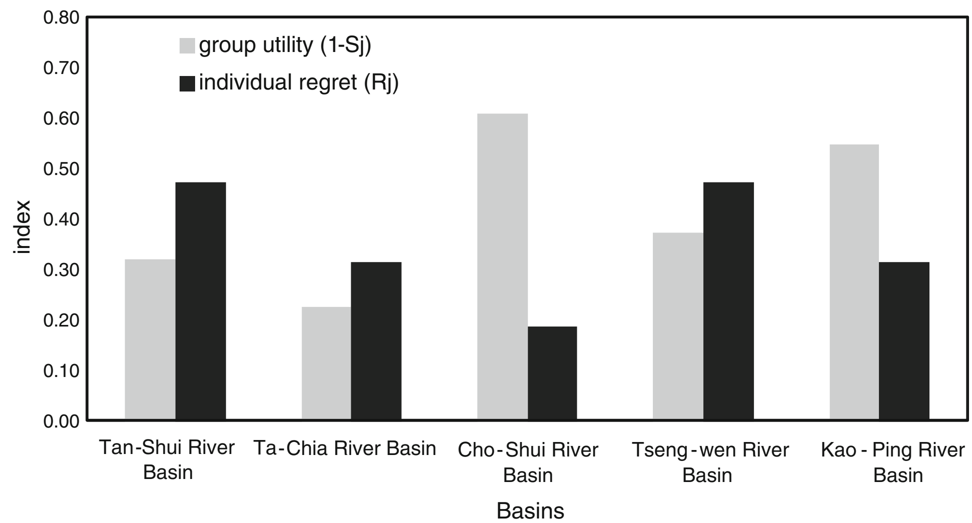

Fig. 2 Measure of each basin's group utility and individual regret

individual regret. In this situation, the Tseng-Wen River Basin has higher environmental vulnerability than the Tan-Shui River Basin and the Ta-Chia River Basin. The environmental vulnerability of the Ta-Chia River Basin is the least among the five basins, when considering the group utility only. Although the landslide area is large in the Ta-Chia River Basin, it can still allow temperate land-use activities, when individual regret is not be considered.

MCA is flexible and can evaluate the problems with numerous factors. The ranking of environmental vulnerability of the five basins are different when only considering the measure of group utility, when only considering the measure of individual regret, and when considering both of them. We cannot say which ranking is the most correct. However, there is no doubt that considering both the group utility and the individual regret of alternatives is more objective. The different ranking scenarios can be useful references for the government's strategies in land-use management.

Conclusion

This study discusses the analysis of basin environmental vulnerability employing two MCA methods. These methods are: the weighted method and the modified VIKOR method. The modified VIKOR method is a compromise method. The main finding and contribution of this study is concluded as follows:

- No matter which MCA method is used, among the five main basins in Taiwan, the environmental vulnerability is the greatest in the Cho-Shui River Basin. Thus, more serious land-use restrictions should be implemented.

- The modified VIKOR method can consider group utility and the individual regret of alternatives. The ranking of basin environmental vulnerability from the weighted method is the same as that of the modified VIKOR method when only considering the measure of group utility.
- The Ta-Chia River Basin should have more serious land-use restrictions than the Tan-Shui River Basin and the Tseng-Wen River Basin, when considering the measure of individual regret.
- The value of v in the modified VIKOR represents the weight of utility measure; $1 - v$ represents the weight of regret measure. When decision makers want to discuss different scenarios, v can be changed accordingly.
- According to the ranking of environmental vulnerability of these basins, classified land-use restrictions can be created. The rankings from different MCA methods may be different and are significant references for the government.

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