

Using the analytical hierarchy process to assess the environmental vulnerabilities of basins in Taiwan

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Abstract Every year, Taiwan endures typhoons and earthquakes; these natural hazards often induce landslides and debris flows. Therefore, watershed management strategies must consider the environmental vulnerabilities of local basins. Because many factors affect basin ecosystems, this study applied multiple criteria analysis and the analytical hierarchy process (AHP) to evaluate seven criteria in three phases (geographic phase, hydrologic phase, and societal phase). This study focused on five major basins in Taiwan: 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. The objectives were a comprehensive examination of the environmental characteristics of these basins and a comprehensive assessment of their environmental vulnerabilities. The results of a survey and AHP analysis showed that landslide area is the most important factor for basin environmental vulnerability. Of all these basins, the Cho-Shui River Basin in central Taiwan has the greatest environmental vulnerability.

Keywords Analytical hierarchy process · Multiple criteria analysis · Environment · Vulnerability analysis

Introduction

Many extreme rainstorms have occurred around the world in recent years. Storms often result in landslides and debris flows, which threaten the local environment and citizens' lives. Environmental conservation is an increasingly important means to protect lives, property, and ecological health. In the past, basin environmental protection usually depended on engineering structures. However, non-structural strategies, such as land-use planning, have become significant methods for basin environment protection (Lu et al. 2001; Wang 2001). Due to urban development, land resources are already scarce and continue to become less available. Land-use activities cannot be entirely prohibited in a basin. Thus, classified land-use management strategies are significant in basin management (Lin et al. 2000; Chang and Lo 2005; Chang et al. 2008a). Environmental policy is usually based on environmental properties such as vulnerability (Villa and McLeod 2002).

Many environmental decision-making and policy-creation processes include one or more vulnerability indicators (VIs). Diverse VIs are applied in different fields (U.S. Environmental Protection

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Agency 1991; Briguglio 1995; Pantin 1997; Kaly and Pratt 2000; Committee 2001; Chang et al. 2008b). VIs always comprise multiple criteria with different effects. Therefore, multiple criteria analysis (MCA) should be applied to integrate the criteria (Opricovic and Tzeng 2004; Tzeng et al. 2005). In order to make valid comparisons in the present study, we adopted a single set of criteria, a single set of criteria weights, and one integration method to calculate VI values for all five basins.

This study focused on five main basins in Taiwan. The objective was to evaluate the various environmental vulnerability levels of these basins. The criteria for the VI were determined from professional opinions obtained by a questionnaire survey. The criteria weights were determined by the analytical hierarchy process (AHP). A weighted average method was applied to integrate the criteria and to calculate the VI values for all five basins.

Methods

Criteria selection

In order to develop the set of criteria for our VI and to select terms suitable for descriptions of basin environments, we reviewed the literature related to environmental vulnerability (Kaly et al. 1999, 2002; Villa and McLeod 2002) and environmental management issues specific to basins (Downs et al. 1991; Mostaghimi et al. 1997; Lu et al. 2001; Wang 2001; Jaspers 2003). In addition, this study gained other information from a survey of professionals. Most studies and professional opinions state that

environmental vulnerability is related to the environmental, economic, and social characteristics of the site. Basin vulnerability was characterized by seven criteria; each criterion was considered in three phases: the geographic phase, the hydrologic phase, and the societal phase. The criteria were: vegetated cover condition, landslide area, soil type, annual average precipitation, extreme storm duration, land-use condition, and population density.

Because these criteria had different units, they had to be transformed to dimensionless indicators on a single scale; this transformation facilitated decision-making on the basis of multiple criteria (Craig and Karen 1995). The criteria were classified into four grades (1, 4, 7, and 10) according to the relative influence of each criterion on vulnerability, as shown in Table 1. The larger the total score of a basin is, the larger the environmental vulnerability of that basin is. The total score of each basin was calculated by the weighted average method. The grades were determined from professional opinions obtained by a questionnaire survey. They are impersonal for basin environmental vulnerability analysis. The weights of all criteria were determined by AHP, as explained in the next section.

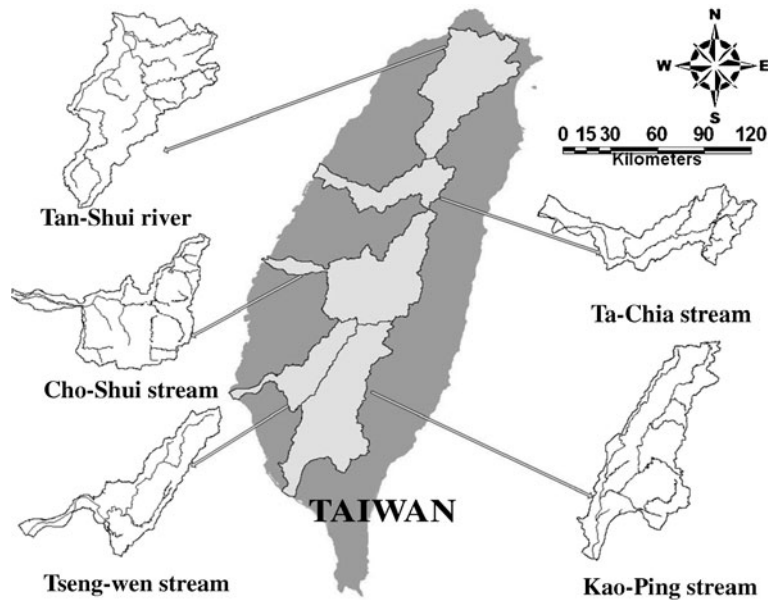
Analytical hierarchy process

The AHP has been widely applied to analyses of problems with multiple criteria. The weights of criteria are determined from comprehensive professional opinions. The weight of each criterion represents its relative importance in the multiple criteria decision-making problem (Saaty 1980,

Table 1 Criteria scores in basin environmental vulnerability analysis

Criteria	Score			
	1	4	7	10
Vegetated cover condition	Excellent	Good	Fair	Bad
Landslide area (ha)	< 1,000	1,000–5,000	5,000–10,000	> 10,000
Soil type	Gravel	Sand	Clay	Silt
Annual average precipitation (mm)	< 2,600	2600–2900	2900–3100	> 3100
Extreme storm duration (day)	< 17	17–18	19–20	> 20
Land-use condition	Forest	Farmland	Park	Urbanized area
Population density (population /km ²)	< 400	400–700	700–1,000	> 1,000

Fig. 1 Location map of the five main basins in Taiwan



1990, 2008). This study applied the AHP method to assess the criteria related to basin environmental vulnerability, and to create a framework for evaluating the relative degree of basin environmental vulnerability. The AHP can simplify a complex system into a series of pair-wise comparisons and a numeric nine-point scale (Noble and Sanchez 1993; Mendoza and Prabhu 2000; Gomontean et al. 2008). The pair-wise comparison technique plays a significant role in the evaluation of the relative weights and importance levels of different criteria. Consistent judgments are necessary for correct application of AHP to multiple criteria decision-making problems; the consistency of the judgments must be verified. The consistency ratio (CR) is calculated to appraise the reliability of the survey; the CR is less than

0.1 when the survey is sufficient and reasonable (Saaty 1990; Noble and Sanchez 1993).

Site description

This study considered five major basins in Taiwan: 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 displays the location map of the five basins. Table 2 presents basic information such as the length of each mainstream and the area of each basin. The Tan-Shui River Basin is located in northern Taiwan. The Ta-Chia River Basin and the Cho-Shui River Basin are located in central Taiwan. The Cho-Shui River is the longest river in Taiwan. The Tseng-wen River Basin and the Kao-Ping River Basin are located in southwestern Taiwan. The Kao-Ping River Basin is the largest basin in Taiwan. These five basins contain a major portion of the water resources of Taiwan.

Table 2 Basic information of the five main basins in Taiwan

Basins	Length of mainstream (km)	Basin area (km ²)
Tan-Shui River	159	2,762
Ta-Chia River	124	1,236
Cho-Shui River	186	3,157
Tseng-Wen River	138	1,176
Kao-Ping River	171	3,257

Results and discussion

Criteria assessment

For the present study, the value of CR was less than 0.1 for comparisons of the importance of the

three phases (the geographic phase, the hydrologic phase, and the societal phase). Therefore, these phases can be reliably compared. Figure 2 shows the relative weights of the geographic phase, the hydrologic phase, and the societal phase. Geographic factors, including vegetated cover condition, landslide area, and soil type, were more important than the effect factors in the hydrologic phase and societal phase.

The values of CR were also less than 0.1 for the relative importance levels of criteria in different assessment phases. Therefore, according to standard AHP practice, the questionnaire survey was reliable. Figure 3a displays the relative weights of vegetated cover condition, landslide area, and soil type in the geographic phase. Likewise, Fig. 3b shows the relative weights of annual average precipitation and extreme storm duration in the hydrologic phase; Fig. 3c illustrates the relative weights of land-use condition and population density in the societal phase. The results show that landslide area is the most important criterion in the geographic phase. Extreme storm duration is more important than annual average precipitation for the evaluation of basin environmental vulnerability. Land-use condition has a greater effect on the vulnerability levels of basin environments than population density.

Table 3 shows the absolute weights of our seven criteria. The absolute weight of the landslide area criterion is about 0.28. It is much larger than other six criteria. Because landslides cause immediate damage to basin environments during rainstorm events, landslides are always regarded as a serious threat. By contrast, the absolute weight of popu-

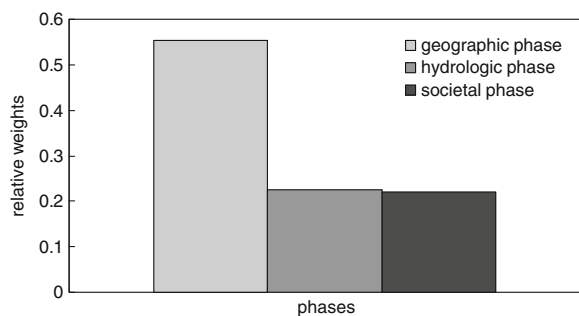


Fig. 2 Relative weights of assessment phases for basin environmental vulnerability analysis

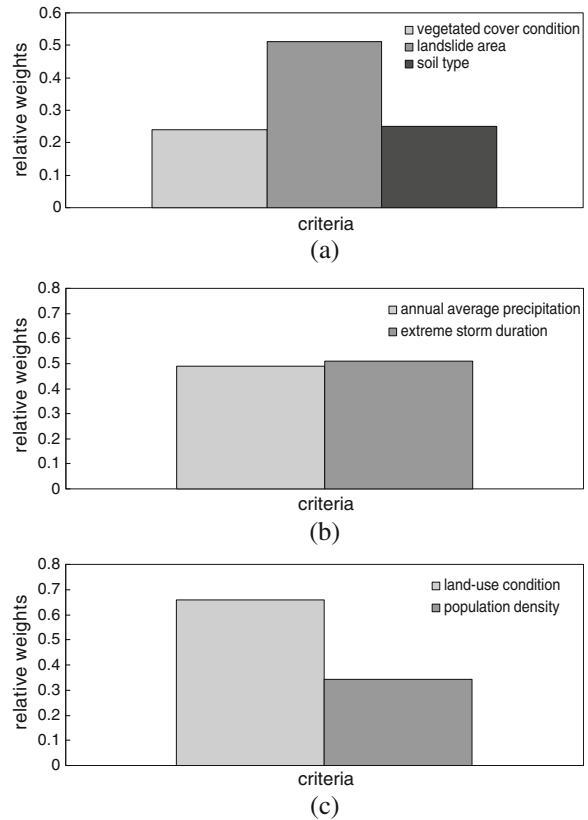


Fig. 3 Relative weights of criteria in each phase of basin environmental vulnerability analysis. **a** Relative weights of criteria in geographic phase. **b** Relative weights of criteria in hydrologic phase. **c** Relative weights of criteria in societal phase

lation density is only about 0.075. This indicates that among all the criteria, population density has the least effect on vulnerability. Although basin vulnerability will increase when population density rises, population density has less direct influence on basin environments than other criteria have. The absolute weights of geographic factors, hydrologic factors, and societal factors are about 0.55, 0.23, and 0.22, respectively. Vegetated cover condition, landslide area, soil type, land-use condition, and population density can change based on land-use planning and environmental management strategies. Therefore, the community can reduce the environmental vulnerability levels of these basins, even though it is not easy to control climatic conditions such as annual average precipitation and the durations of extreme storms.

Table 3 Absolute weights of criteria in basin environmental vulnerability analysis

Phases	Criteria	Absolute weights	Importance
Geographic factors	Vegetated cover condition	0.133	4
	Landslide area	0.283	1
	Soil type	0.138	3
Hydrologic factors	Annual average precipitation	0.111	6
	Extreme storm duration	0.115	5
Societal factors	Land-use condition	0.145	2
	Population density	0.075	7

Environmental vulnerability analysis

This study combined quantitative information on landslides, population densities, and hydrologic factors and qualitative information on vegetated cover condition, soil type, and land-use condition. Table 4 shows the properties of the five relevant basins. The environment properties of the five basins shown in Table 4 are average conditions. All quantitative information and qualitative information were provided by the Taiwanese government.

Vegetated cover condition is good in these basins. The minor differences between vegetated cover conditions among these basins were deemed insignificant for purposes of the present study. All basins were assigned a score of 4 for vegetated cover condition. The landslide area in the Cho-Shui River Basin is more than 10,000 ha, which greatly exceeds the landslide areas of the other four basins. Therefore, the landslide area score for the Cho-Shui River Basin was 10. All five of the examined basins had the same type of sandy soil and forested land usage, and all five were assigned

scores of 4 and 1 for soil type and land-use condition, respectively. Because unusually high annual average precipitation values were found in the Tan-Shui River Basin and the Kao-Ping River Basin, the annual average precipitation scores of both of those basins were 10. Because extreme storms in southern Taiwan tend to have longer durations than in northern or central Taiwan, the Tseng-Wen River Basin and the Kao-Ping River Basin were assigned scores of 10 for extreme storm duration. The largest population density of all the studied basins was found in the Tan-Shui River Basin, and the corresponding population density score was 10.

For each basin, Table 5 shows individual scores, total score, and ranking. Each basin’s total score represents the degree of that basin’s environmental vulnerability. The larger the total score is, the larger the basin environmental vulnerability is. The Cho-Shui River Basin was the most vulnerable; the second most vulnerable basin was the Kao-Ping River Basin; the third and fourth were the Tseng-Wen River Basin, and the Tan-Shui River Basin; the Ta-chia River Basin was

Table 4 Environmental properties of the five main basins in Taiwan

Criteria	Basin environment properties				
	Tan-Shui river	Ta-Chia stream	Cho-Shui stream	Tseng-wen stream	Kao-Ping stream
Vegetated cover condition	Good	Good	Good	Good	Good
Landslide area (ha)	313	4,178	11,279	625	3,413
Soil type	Sand	Sand	Sand	Sand	Sand
Annual average precipitation (mm)	3,172	2,376	2,353	3,005	3,139
Extreme storm duration (day)	15	17	20	21	22
Land-use condition	Forest	Forest	Forest	Forest	Forest
Population density (population /km ²)	1,769	305	374	624	384

Table 5 Vulnerability indicator values for the five main basins in Taiwan

Criteria	Absolute weights	Score				
		Tan-Shui river	Ta-Chia stream	Cho-Shui stream	Tseng-wen stream	Kao-Ping stream
Vegetated cover condition	0.133	4	4	4	4	4
Landslide area	0.283	1	4	10	1	4
Soil type	0.138	4	4	4	4	4
Annual average precipitation	0.111	10	1	1	7	10
Extreme storm duration	0.115	1	4	7	10	10
Land-use condition	0.145	1	1	1	1	1
Population density	0.075	10	1	1	4	1
Total score		3.49	3.01	5.05	3.74	4.70
Ranking of basin environmental vulnerability	4	5	1	3	2	

the least vulnerable. Landslide area is the most important criterion in basin environmental vulnerability analysis. The Cho-Shui River Basin has a much larger landslide area than the other basins. Thus, the Cho-Shui River Basin has the largest environmental vulnerability among these basins according to the multiple criteria decision-making framework created by our AHP. Rainfall characteristics and other hydrologic properties in southern Taiwan present grave challenges. Typhoons that strike southern Taiwan usually result in serious damage. Hydrologic-phase criterion scores for the Kao-Ping River Basin and the Tseng-Wen River Basin are larger than those of other basins. Therefore, the environmental vulnerability levels of southern basins are higher than those of basins in northern Taiwan.

Conclusions

Basin environmental vulnerability is an important contemporary issue in sustainable environmental management. Any VI should consider a comprehensive range of effect factors. Thus, basin environmental vulnerability is a multiple criteria decision-making problem. This study collected information from literature and professional opinions to create a framework for basin environmental vulnerability analysis. The present study's VI summarized seven criteria throughout a geographic phase, a hydrologic phase, and a societal phase. This study based its research on a survey of professionals and examined the situation using

MCA by the AHP method. The major findings of this study can be stated as follows:

1. The set of VI characteristics of basin environments include: vegetated cover condition, landslide area, soil type, annual average precipitation, extreme storm duration, land-use condition, and population density.
2. The effect factors in the geographic phase are more important than hydrologic factors and societal factors.
3. The landslide areas of basins are highly related to basin environmental vulnerability.
4. The Cho-Shui River Basin in central Taiwan has the highest environmental vulnerability of the studied basins.
5. Environmental vulnerability levels for basins in southern Taiwan are higher than environmental vulnerability levels for basins in northern Taiwan.

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