

# A CASE STUDY OF VULNERABILITY ASSESSMENT IN THE SEDIMENT HAZARDOUS AREA BY DECISION ANALYSIS

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The proper direction toward development or mitigation of the disaster risk reduction plan (DRRP) is a pressing problem. This study focuses on this problem to estimate the regional vulnerability based on the current data and its implications on the proper DRRP direction in terms of multi-criteria decision method. A catchment with high frequency of sediment disasters in central Taiwan was determined as the study area and divided into 9 sub-areas. To proceed with this method, several criteria under the two main constrains, development and regional vulnerability were considered. 5 criteria are calculated from the data include land use data, the current government policy, the economical and social data, and the mitigation controlling measure efficiency. The results show the most appropriate solutions in the most stable situation. Some directions match with current land use regulations of 9 sub-areas. This result can be applied as an example and direction for the sediment disaster DRRP in the catchment scale.

*Key Words: mitigation, disaster risk reduction plan, multi criteria decision making, vulnerability*

## 1. INTRODUCTION

A rarely heavy rainfall brought by the typhoon Morakot 2009 caused significant losses on property as well as human deaths in the Southern Taiwan. Some debris flows and landslides were triggered by heavy rainfall that accumulated to 2004 mm from August 6<sup>th</sup> to August 8<sup>th</sup>. Sediment disasters during and after typhoon included 400 people are covered by landslides in Kaoshung County<sup>1)</sup>. It was due to this typhoon that some problems on emergency response were determined. The direction and content of mitigation program for sediment disasters became the main object of discussion, such as land use regulations, the insufficiency in the Disaster Response/Rescue Act, and the response and connection between governments<sup>2), 3)</sup>.

The Disaster Response/Rescue Act was instituted after the 1999 earthquake disaster in Taiwan. There are two distinct directions of the mitigation program during the period from 1999 to 2008, according to the Disaster Risk Reduction Plan Manual published by the Soil and Water Conservation Bureau (SWCB) of Taiwan<sup>4)</sup>. From

1999 to 2004, main measures and strategies were focused on mitigation and recovery from the earthquake disaster. On the other hand, the period from 2004 to 2008, deviates the emphasis on developing villages as tourist locations depending on indigenous natural conditions. Elsewhere, some areas were designed as soil and water conservation areas and restricted development activities and the settlements. However, crucial hill slope areas are still directed to the government policy of development due to the insufficiency of land use regulations. The disaster brought about by Morakot not only clarified this issue but also triggered the discussion regarding the consideration within the disaster risk reduction plan of the two conflicting targets for the hill slope area such as development and mitigation.

This study is looking into these two concepts: development and mitigation of sediment disaster. We intend to evaluate a most appropriate solution for a small catchment which consists of alternatives including development and mitigation. It is a multi criteria problem as it is necessary to decide the direction of the disaster risk reduction plan that can

be influenced by many factors. Multi criteria decision analysis (MCDA) is a method to solve the problem with two or more criteria used in many kinds of sphere and studies. Gamper<sup>5)</sup> evaluated the cost and benefit for management measures to judge the best alternative by cost benefit and multi criteria; Chou<sup>5)</sup> evaluated the willing to pay (WTP) value to the earthquake disaster by MCDA. These studies shows a reasonable result from the factors which were selected. However, it has not applied to the mitigation program for sediment disasters.

From these reasons referred above, we intend to figure out a framework to describe which areas are more appropriate for development or for mitigation in a catchment scale. To evaluate it, several criteria and sub criteria are selected. In the beginning, the sub-area vulnerability is clarified; based on the result referred in the first step, the MCDA are held and the best solution for this catchment is list according to the maximum criteria scores.

## **2. STUDY AREA AND FLOW SIMULATION TOOL**

### **(1) Study area and steps**

The Chenyoulanxi catchment is located in the Central Taiwan. It is one of the main tributaries of the Zhuoshuixi River and is highly frequency on sediment disasters because of the weak geologic conditions and the serious soil erosion on the steep hill slope<sup>6)</sup>. Based on the geological and topographical conditions, a landslide susceptibility map was evaluated in the previous study<sup>7)</sup>. This map represented the major effect of the landslide susceptibility is the geological condition.

In recent years, controlling measures, including structured and non-structured, were built in this catchment due to the high frequency of sediment disasters. In the government strategies, some areas were designed to improve their economics, such as the tourist spots and agriculture. Moreover, three sub catchments were designed as the soil and water conservation areas and budgets were particularly drawn up for decreasing the vulnerable factors. Meanwhile, 35 torrents in this catchment has been defined as potential debris flow torrents<sup>6)</sup> from 1996, according to the investigation reports by the Soil and Water Concentration Bureau (SWCB) and were classified into three dangerous levels.

In the land use categories, most of the areas are classified as forest, occupying 40,818 ha; where the roadway and local community is distributed along the rivers and torrents. The main industry in this region is agriculture, occupying 2,178 ha. In the population structure, 30% of the population is either elder (over 65 years old) or children (younger than

15 years old) which is about 4,960 people. In order to compare the recent development trend in the catchment and to use MCDA, 9 sub-areas in the catchment are classified based on the geological condition and river and torrents locations (**Fig.1**).

### **(2) Vulnerability Assessment Framework**

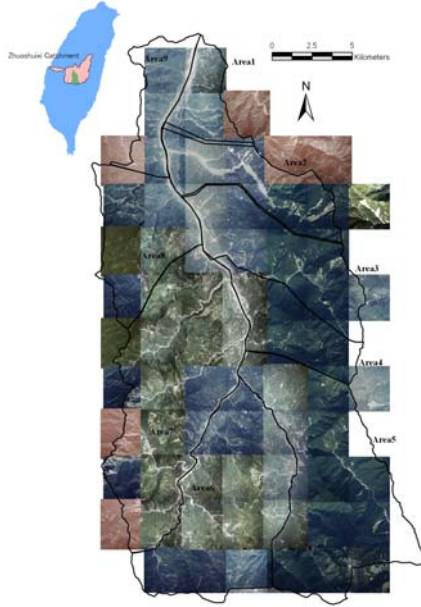
Vulnerability Index reflects how possible vulnerable factors may trigger disaster. According to the previous study<sup>1)</sup>, vulnerability framework can be classified into several levels based on the objects that are focused on. The considered scales are government and the regional communities (smaller than a general village) due to the sub-areas we defined earlier.

The key factors for evaluating community vulnerability were referred by many studies. We employed two of them mentioned by Wu<sup>8)</sup> and Zheng<sup>9)</sup>, which include biophysical, social, and environmental vulnerability and exposure. Biophysical factor shows the original fragile environmental situation. It is shown in terms of the current disaster spots in the area exposed by a specific natural hazard. Social factor is the social and economical factors that related to the regional communities. Environmental factor is determined by the environmental condition of the regional communities. In addition to these three factors, exposure is also considered. Because it shows how much individual, household, or property in a region is exposed to a certain natural hazard, exposure is usually employed as an important factor represented by probability.

### **(3) Multi Criteria Decision Method**

People always face the problems with multiple goals or conflict purposes and need to make decisions. In order to compare and to judge which decision is the most appropriate one among those alternatives, multi criteria decision method (MCDM) is developed and used in this study. It includes many kinds of different techniques, which can be divided into the following two methods; multi-objective programming method (MOP) and multiple objective decision making (MODM). Technique for order preference by similarity to ideal solution (TOPSIS) is one of MOP method developed by Hwang and Yoon and Lai et al.<sup>10)</sup>. It is invented based on the concept that the acceptable solution should be closed to ideal solution<sup>11)</sup>. This method is normally used when the criteria can be quantified. The best solutions are determined by the ideal solution and negative ideal solution in this method.

A framework for MCDM should be referred firstly, which includes goals, criteria, and



**Fig.1** The nine subarea of Chenyoulanxi catchment with aerial photographs

sub-criteria. It is established by Analysis Hierarchy process (AHP) and can help to clarify the complicated problems in a systematic way. Four steps are proceeded later; they are (i) calculating sub-criteria scores, (ii) standardize sub-criteria scores, (iii) calculating the ideal and negative ideal solution scores, (iv) calculating the distance from each alternative to the ideal and negative ideal solutions and selecting the minimum distance as the best alternative.

Criteria were measured in different units. To use all of the criteria in one assessment, they are standardized in terms of equations as follows<sup>(12), (13)</sup>,

$$x_i^* = \frac{\max(x_i) - x_i}{\max(x_i) - \min(x_i)} \quad (1)$$

where the  $x_i$  is considered to be positive result,

$$x_i^* = \frac{x_i - \min(x_i)}{\max(x_i) - \min(x_i)} \quad (2)$$

where the  $x_i$  is considered to be negative result. In the Eqs. (1) and (2),  $x_i$  are the measured criterion value for the  $i_{th}$  farming system and  $x_i^*$  is the standardized value of  $x_i$ .

The ideal and negative ideal solutions are calculated after sub-criteria scores are standardized. The ideal and negative ideal solution scores are composed to decide the Petero-optimal front. With this front, the best alternative can be decided when  $L_j$  is the smallest.  $L_j$  is the distance between the ideal and negative ideal alternatives, and is calculated as follows<sup>(5)</sup>;

$$L_j = \left[ w_1^2 \left| \frac{g_1^* - g_{1,j}}{g_1^* - g_{1,w}} \right|^2 + w_2^2 \left| \frac{g_2^* - g_{2,j}}{g_2^* - g_{2,w}} \right|^2 \right]^{1/2} \quad (3)$$

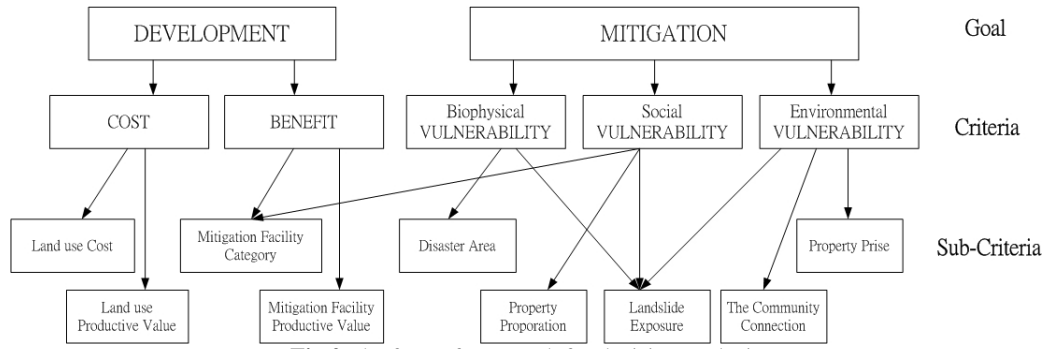
where  $w_i$  is the weighting of the  $i_{th}$  goal,  $g_{i,j}$  is the measured criterion value for the  $i_{th}$  farming system and  $j_{th}$  probable alternative,  $g_i^*$  is the best criteria value of  $i_{th}$  criteria,  $g_{i,w}$  is the worst criteria value of  $i_{th}$  criteria, and  $i$  equal to 1 and 2.

### 3. GOAL, CRITERIA AND DATA

A framework including goal, criteria, and sub-criteria is listed in **Fig.2**. The goals should be more than two and are conflict to each other. In this study development and mitigation are determined because both two are the main considerations when governments designing the mitigation program. However, these two goals are not conflict. Then vulnerability is determined instead of mitigation because mitigation is necessary where vulnerability is getting increased. Accordingly, in this assessment we expected that the development benefit is maximum or vulnerability value is minimum. 5 criteria below the two main goals are determined to calculate the scores via sub-criteria in the third layer; (i) cost and (ii) benefit under development, (iii) biophysical vulnerability, (iv) social vulnerability and (v) environmental vulnerability under mitigation.

On the other hand, the alternatives are determined by current policies, tourist agriculture, maintenance as agriculture area, and the soil and water conservation area. Three of them and 9 sub-areas are composed of 19,683 alternatives. The tourist agriculture is commercial direction, which intends to increase the tourists and other developments based on the agricultural activities. It also increases the probability of sediment disaster, on the other hand. The maintenance as agriculture area is to preserve the agriculture activities and to design some of the disaster controlling measures at the same time. The proportion of development and mitigation can be thought as half and half. The soil and water conservation area designed for the area sensitive to the hazards<sup>(13)</sup>. The development activities are restricted for decreasing the stress to the environment. The developed benefit is few when somewhere is design as soil and water conservation area.

Nine sub-criteria for calculating criteria are determined, including landslide susceptibility, land use cost and productive value, the mitigating facilities cost and productive value, the property and life proportion and prise, the regional community connection, and the disaster areas. The relationship between goals, criteria, and sub-criteria are shown in **Fig.2**.



**Fig.2** The factor framework for decision analysis

Five criterias are the main criteria to generate the scores for each alternative, they are calculated by the equations as follows,

a. Cost ( $C_i$ ) — It is the development costs. The development costs of land uses and mitigation facilities are determined and shown as follows;

$$C_i = \sum_{m=1}^4 (L_m + M_m) A_m \quad (4)$$

where  $L_m$  is the average cost of each land use category;  $M_m$  is the average mitigation facilities costs of the area;  $A_m$  is area of sub-area, and  $m$  shows the different land use, including house, roadway, farms, and forest.

b. Benefit ( $B_i$ )— It includes the benefits can be contained after development, it is calculated as follows;

$$B_i = \sum_{m=1}^4 (L_p + M_p + G_p) \times A_m \quad (5)$$

where  $L_p$  is the average productive value of each land use;  $M_p$  is the average productive value of the mitigation facilities;  $G_p$  is the average budget got from the government.

c. Biophysical Vulnerability ( $V_b$ )— Accroding to its definition. We determined the current sediment fragile conditions from landslide and debris flow, which include the proportion of landslide areas and the debris flow torrents. Debris flow torrents are considered of dangerous level index of potential debris flow torrents and affected residents defined by government. This part is calculated as follows;

$$V_b = \sum_{m=1}^4 (LS_a \times A_m) + DB_m \quad (6)$$

where  $LS_a$  is the average susceptibility of landslide area and the subarea;  $DB_m$  is the total dangerous level of debris flow in each subarea.

d. Social Vulnerability ( $B_i$ ) — It includes the social and economical conditions inside the sub-area. The total property value, including forest, farms, roadway, and building, the proportion of disaster weaker (people younger than 15 years old and elder than 65 years old), and the relative index of income and saving of each household per year are considered. It is shown as follows;

$$B_i = \sum_{m=1}^4 (P_w + P_c) \times A_m + P_h \times S_m \quad (7)$$

where  $P_w$  is the disaster weaker density of each sub-area;  $P_c$  is the prize of each land use categories;  $S_m$  is the average income and saving per person;  $P_h$  is the people number between 15 and 65 years old.

e. Environmental Vulnerability ( $E_b$ )— It focuses on the environmental conditions of sub-areas. The transportation situations and the distance from each building to the significant facilities are determined. The transportation situations includes the building area is inside the roadway effective range, which is referred as 100m, and the transportation ratio, which is the ratio of roadway effective range and the total sub-area. The significant facilities includes temple and school because they were referred as temporary shelter in many villages. Here the average distance from each building to the nearest significant facility is calculated. The  $E_b$  is generated as follows;

$$E_b = -C_c - T_n + D_{ts} \quad (8)$$

where  $C_c$  is the connections inside the subarea;  $T_n$  is the transportation connections in the whole area;  $D_{ts}$  is the average distance of each subarea from each building to the nearest important facilities, including temples and schools.

The vulnerability score for each sub-area will be generated by summing up the three vulnerability part scores. Before summing up them, each of the vulnerability part scores will be standardized.

## 4. RESULT AND DISCUSSION

### (1) Vulnerability of the study area

Vulnerability of each sub-area was evaluated in terms of the data in the period of 2001 to 2006. The results are shown in **Table 1**.

a. Biophysical vulnerability: It presented the real sediment disaster situations in each sub-area, including the landslide area in 2004 and the dangerous level of the 35 torrents determined by government. From this part, sub-areas 1, 7, and 9 have the highest score, reflecting the area with the most landslide areas and debris flow

torrents. Furthermore, the sub-area 4 has the lowest score due to most of the areas are forests without any development.

- b. **Social Vulnerability:** It shows the social situation from the property and the applied wealth. Some areas are not many communities or properties, but the income and saving is high, which helps to decrease the vulnerability score.
- c. **Environmental Vulnerability:** It represents the transportation situation in each area. Sub-areas 1, 2, 6, and 7 are more developed. Accordingly, the proportion of roadway and the full area is also high. This part also explained the development is not simply a negative factor. More residents can be connected with important facilities or the other areas.

Vulnerability score for each sub-area is calculated by multiplying the sum of three parts and landslide susceptibility which was evaluated in the previous study<sup>7)</sup>. The vulnerability scores are the relative scores comparing within 9 sub-areas. From **Table 1**, Sub-areas 7 and 9 have the highest vulnerability scores and sub-areas 8 and 5 have the lowest. The higher positive value means more vulnerable to the sediment disaster. In the table, negative value means the criteria has positive effect to the sediment disasters, i.e. vulnerability will be decreased under condition from that criteria.

## (2) The best solution

The ideal and negative ideal solutions are calculated firstly as the standards for determining the best solution. Development and mitigation scores of 19,683 solutions were calculated from the five criteria scores (**Fig.2**). We considered the best solution under the weighting ratio of development and mitigation was determined as equaly. It is the most stable situation because the determined solution will not be affected by other factors easily. The best two solutions were selected when the distances with the ideal solution are 0.5263 and 0.5262. The 0.5263 one is listed because the difference between two solutions imply simply the different land use condition on sub-area 3 and on the other hand, because of less affected people. In **Fig.3**, the appropriate directions to decrease vulnerability for 9 sub-areas are shown.

From **Fig.3**, sub-area 1 is available to design as soil and water conservation areas and other sub-areas are available to maintain the agriculture activity. The numbers in the sub-areas are their vulnerability score from **Table 1**.

In the historical record, there were serious sediment disasters occurred in sub-areas 1, 2, 5, 6, and 7. Besides, there are several tourist spots in sub-areas 3, 7 and 8, and part of areas in sub-areas 3,

6, and 7 were designed as soil and water conservation areas at the present. Based on the vulnerability assessment result in **Table 1**, sub-areas 1, 3, and 5 are available to maintain agriculture with engineering controlling measures due to fragile environmental conditions; sub-areas 4, 8, and 9 are available to develop due to only high vulnerability score in social vulnerability part; sub-areas 2, 6, and 7 should be restricted the development activities. The result of the MCDA proved that it is necessary to maintain the agriculture in most of the sub-areas, vulnerability could be decreased with the well-prepared engineering and non-engineering strategies. However, it does not show the appropriate strategies in the sub-areas which are should be protected.

**Table 2** shows the criteria values of the best solution in currency. The net development benefit could be obtained from the benefit value and the cost value, occupying USD 50 million in total. Meanwhile, vulnerability value is the sum of biophysical and social factors, occupying USD 22.16 million in total. The biological vulnerability was not considered in this evaluation because the environmental fragile condition is the natural condition which does not changed with different alternatives. This result shows that when this solution is determined, there are 7,1 million dollars equivalent vulnerability should be decreased and there will be 16,501 people threaten by sediment hazard. Besides, it also represents the best solution under the conditions during 2001 to 2006 and it is the safest solution. The result may be different when using the different weightings sets or different data.

## 5. CONCLUSION

This study described an vulnerability assessment method and a MCDA evaluation result in catchment scale. The conclusions are drawn as follows;

(1) Vulnerability of Chenyoulenxi catchment can be evaluated from biophysical, environmental, and social vulnerability and landslide susceptibility. The biophysical vulnerability shows the fragile condition of sediment disasters in the sub-area. Social vulnerability shows the social factor inside the sub-areas from the property, resident amount and their welfare. Environmental vulnerability shows the environmental factor of the sub-area. The transportation and significant facility are considered. These valuables successfully described vulnerability distribution in the target catchment.

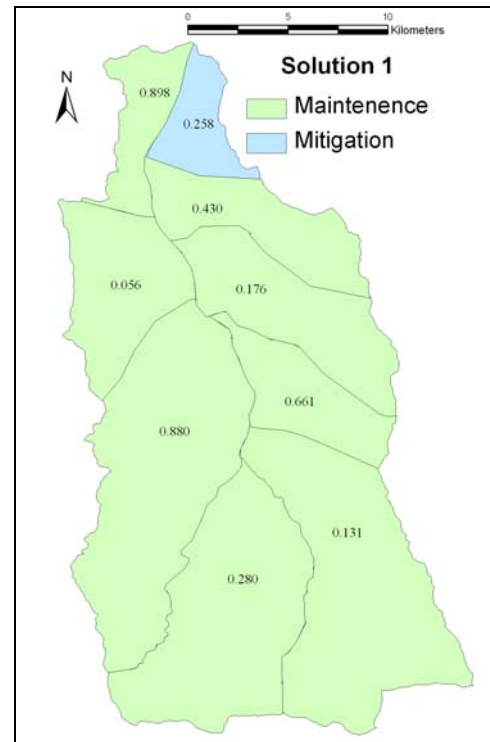
(2) From the vulnerability assessment result, some of the valuables the positive effect to the sediment disaster, such as income and salary,

**Table 1 Vulnerability score of each sub-area in the catchment**

Sub-area	1	2	3	4	5	6	7	8	9
Landslide area proportion	0.856	0.461	0.295	0.126	0.238	0.000	0.237	0.138	1.000
Debris flow dangerous level	1.000	0.381	0.291	0.000	0.564	0.364	0.600	0.164	0.309
Biophysical Vulnerability	1.856	0.842	0.586	0.126	0.802	0.364	0.837	0.302	1.309
Property amount	0.336	0.319	0.139	0.000	0.235	0.305	1.000	0.203	0.035
People amount	0.335	0.324	0.142	0.000	0.241	0.288	1.000	0.205	0.035
Income and Saving	-1.000	-0.000	-0.454	-0.031	-0.734	-0.104	-0.014	-0.632	-0.152
Social Vulnerability	-0.329	0.644	-0.173	-0.031	-0.258	0.489	1.986	-0.244	-0.083
Community Connections	-0.315	-0.284	-0.100	-0.000	-0.228	-0.299	-1.000	-0.130	-0.027
Community Transportation Connections	-0.656	-0.190	-0.080	-0.045	-0.039	-0.294	-0.304	-0.133	-0.061
Important Facility Distance	0.160	0.099	0.201	1.540	0.000	0.319	0.329	0.320	1.000
Environmental Vulnerability	-0.811	-0.375	-0.021	1.495	-0.267	-0.274	-0.975	0.057	0.912
Exposure	0.360	0.387	0.406	0.416	0.473	0.484	0.476	0.486	0.420
Total Vulnerability	0.258	0.430	0.176	0.661	0.131	0.280	0.880	0.056	0.898

**Table 2 The value of the best solution**

Criteria	Value
Cost (dollars)	13,859,000
Benefit (dollars)	63,936,888
Social Vulnerability (dollars)	21,379,177
Environmental Vulnerability (dollars)	785,448
Affected Population (persons)	16,501



**Fig.3** The best solution for the catchment and vulnerability score of each sub-area

community transportation connection, and community connection. These valuables represent that vulnerability score could be decreased by some spatial conditions, such as the sub-areas located in the convenient areas or with more populations.

(3) Two results from MCDA assessment were determined as the best solutions by current data and the same weightings of the two principal goals. In the best solution, the sub-area 1 is suggested as protective area and others are maintainance of agriculture. The result shows the solution under the most stable condition, which will not affected by other valuables or by decision maker preference.

This study accomplished the work on evaluating the best solution for the sediment disaster prone area. This method helps decision makers to arrange the suitable directions for the mitigation program relevant for small catchment areas.

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## REFERENCES

- 1) Fire Agency: Response reports of Makorot Typhoon, 2009.
- 2) Ho, C.C.: An analytical study of local bureaucracy in disaster from Taipei city hall, Master Thesis, 2003

- 3) Shi, B.C. and Chang, S.Y.: The introduction and exmination of Taiwanese disaster rescue and response system, The journal of Civil and Hydraulic Engineering, 36 (4), 52-58, 2009 (in Chinese)
- 4) Soil and Water Conservation Bureau, Soil and Water Conservation Manual from 1999 to 2008.
- 5) C. D. Gamper, M. Thöni, and H.Weck-Hannemann: A conceptual approach to the use of Cost Benefit and Multi Criteria Analysis in natural hazard management, Nat. Hazards Earth Syst. Sci., 6: 293-302, 2006
- 6) Chou, S.H.: Study on Earthquake Risk and Land Use management, Doctoral dissertation, 2004 (in Chinese)
- 7) Chen, Y.J.: Using spatial information technology to quantify the volume of debris flow in the watershed of Chenyoudenxi stream, Master thesis, 2004 (in Chinese).
- 8) Wu, T.Y. and Takara, K.: Development of a hazard mapping method for debris flow in disaster-prone areas, Annual Journal of Hydraulic Engineering, JSCE, 52, 145-150, 2008.
- 9) Wu, T.Y. and Takara, K: The Framework of Vulnerability and Assessment of Exposure using Landslide Hazard Mapping, DPRI annual, 51b: 75-82, 2009.
- 10) Zheng, N.S.: Quantitative Assessment of Vulnerability for Large-Scale Flood Hazard with Remote Sensing and GIS, 2009, doctoral dissertation.
- 11) Olson, D.L.: Comparison of Wiegths in TOPSIS Models, Mathematical and Computer Modelling, 40, 721-727, 2004.
- 12) Wu, Z.L.: The application and statement of Multi criteria analysis method, the symposium of management decision making methods, 2008 (in Chinese).
- 13) Prato T. and Herath, G.: Multiple-Criteria Decision Analysis for Integrated Catchment Management, 2006, [www.deakin.edu.au/buslaw/aef/workingpapers/papers/200630eco.pdf](http://www.deakin.edu.au/buslaw/aef/workingpapers/papers/200630eco.pdf)
- 14) Ko, Y. C.: Policy Implementation Analysis of the Designated Soil and Water Conservation Area Management, Doctoral dissertation, 2007 (in Chinese) .

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