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Assessment of the Vulnerability and Risk of Climate Change on Water Supply and Demand in Taijiang Area

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***Abstract*—**The development of sustainable utilization water resources is crucial. The ecological environment and water resources systems form the foundation of the existence and development of the social economy. The urban ecological support system depends on these resources as well. This research studies the vulnerability, criticality, and risk of climate change on water supply and demand in the main administrative district of the Taijiang Area (Tainan City). Based on the two situations set in this paper and various factors (indexes), this research adopts two kinds of weights (equal and AHP) to conduct the calculation and establish the water supply and demand risk map for the target year 2039. According to the risk analysis result, which is based on equal weight, only one district belongs to a high-grade district (Grade 4). Based on the AHP weight, 16 districts belong to a high-grade or higher-grade district (Grades 4 and 5), and from among them, two districts belong to the highest grade (Grade 5). These results show that the risk level of water supply and demand in cities is higher than that in towns. The government generally gives more attention to the adjustment strategy in the "cities." However, it should also provide proper adjustment strategies for the "towns" to be able to cope with the risks of water supply and demand.

***Keywords*—**Climate change, risk, vulnerability, water supply and demand.

I. Introduction

HISTORICAL records of flood, drought, and hydrologic data in Taiwan in the past 30 years show that the change in hydrology and typhoon intensity tended to become strong. Records also show that flood alternates with drought and their frequencies are becoming more intensive, thus leading to disasters that are more serious. For example, after typhoons Toraji and Nari hit the country in 2001, a serious drought occurred in 2002. In 2004 after the drought, Mindulle and Aere followed. The next year, Haitang and Talim landed, and then a drought occurred in 2006. Typhoon Bilis also arrived at the same time. From 2007 to 2008, Sepat, Krosa, Kalmaegi, Fung-wong, Sinlaku, and Jangmi hit the country. The drought in 2009 ended with typhoon Morakot, but a drought occurred in 2010. The alternate occurrences of flood and drought have become normal phenomena.

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According to the report of the Intergovernmental Panel on Climate Change (IPCC), the global temperature is rising, which may make flood and drought more serious. Taiwan is located at a high-risk region, and the impact of climate change should be carefully studied. Therefore, the assessment of the vulnerability and risk of climate change on water resources and flood is necessary. The preparation of risk maps can provide important references in making adjustment strategies for climate change and planning in the future.

II. Theories and Methods

A. Vulnerability Index and Criticality Index of Water Supply and Demand

The UNDP [1] and the UNEP [2] recommends the adoption of the renewable supply and flow, water consumption, surface water stock, runoff, and drought period/area that for the vulnerability index of water resources. However, these indexes consider only water resources but not the demand. Therefore, based on the drought vulnerability index put forward in [3], this research divides the indexes into three vulnerabilities of water, namely, industrial, domestic, and agricultural. The index of the vulnerability of industrial water includes industrial water consumption (water withdrawal per unit of GDP), number of industrial enterprises, and value of industrial output. The index of the vulnerability of domestic water includes domestic water consumption (domestic water consumption per capita per day), population density, and number of people using water. The index of the vulnerability of agricultural water includes the water consumption (water duty) and the agricultural area. This research analyzes the criticality index with the system dynamic model, which includes the deficiency ratio of domestic, industrial, and agricultural water. Based on the water deficiency ratio, this research investigates and analyzes the losses of domestic, industrial, and agricultural water shortage.

This research analyzes the water supply and demand risk maps based on two layers: vulnerability ($I_{(1)}$) and criticality ($I_{(2)}$). Vulnerability is subdivided into exposure and disaster-resistance as shown in Fig. 1. Every layer is constructed and quantized by using several appropriate indexes. There are 11 index values in total.

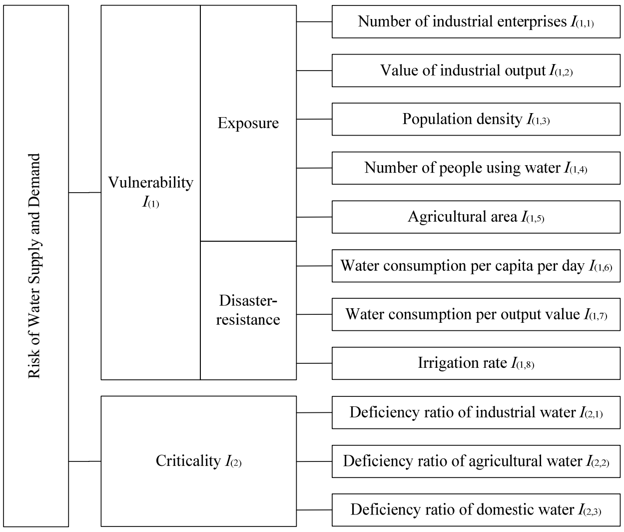


Fig. 1 Hierarchy map of risk assessment of water supply and demand

- Number of industrial enterprises ($I_{(1,1)}$) refers to the number and types of factories within the planned area. A larger index value reflects the stronger demand for water and higher relative vulnerability.
- Value of industrial output ($I_{(1,2)}$) refers to the types and annual output value of the factories within the planned area. Obtaining such data to some degree is difficult, hence it was replaced by "enterprise remuneration," which is defined as enterprise remuneration = profit + bad debt loss and transfer payment + other non-operating expenditure – investment of income other non-operating income and surplus from selling assets. The larger this index value, the stronger is the demand for water and a higher relative vulnerability.
- Population density ($I_{(1,3)}$) is the ratio of population in an area (neighborhood) over the area of such area (neighborhood). The larger index value means bigger water consumption and higher relative vulnerability.
- Number of people using water ($I_{(1,4)}$) refers to estimated quantity of people using water within the planned area. The larger index value means stronger demand for water and higher relative vulnerability.
- Agricultural area ($I_{(1,5)}$) refers to the investigated area of the agricultural site or the area of the cultivated land within the planned site. The larger index value means stronger demand for water and higher relative vulnerability.
- Water consumption per capita per day ($I_{(1,6)}$) refers to the calculated domestic water consumption per capita per day. The calculation method is as follows: water consumption per capita per day (liter) = total annual domestic water consumption (ton) ÷ number of people using water ÷ 365 (or 366) ×1000. The larger index value means stronger demand for water and higher relative vulnerability.
- Water consumption per output value ($I_{(1,7)}$) refers to the investigated or estimated various types of water consumption of factories within the planned area and their output value. The larger index value means stronger demand for water and higher relative vulnerability.
- Irrigation rate ($I_{(1,8)}$) is the irrigated area per water flow (enter into the field), and the unit is in ha/cms. During the irrigation period, the water duty will be affected by the value of k (infiltration), roughness index of channel (n), and other factors. The equation is water duty (E) = area (A)/water flow at the intake (without any loss) (Q). The larger index value means stronger demand for water and higher relative vulnerability.
- Deficiency ratio of industrial water ($I_{(2,1)}$) is the percentage of total industrial water shortage over the planned water demand in a certain period. If the client has the behavior of saving water, the planned water demand will be affected during the water-saving period. The larger index value means stronger demand for water and higher relative vulnerability.
- Deficiency ratio of agricultural water ($I_{(2,2)}$) is the percentage of total agricultural water shortage over the planned water demand in a certain period. If the client has the behavior of saving water, the planned water demand will be affected during the water-saving period. The larger index value means stronger demand for water and higher the relative vulnerability.
- Deficiency ratio of domestic water ($I_{(2,3)}$) is the percentage of total domestic water shortage over the planned water demand in a certain period. If the client has the behavior of saving water, the planned water demand will be affected during the water-saving period. The larger index value means stronger demand for water and higher the relative vulnerability.

An index code is given to every index $I_{(i,j)}$ as defined above. The corner mark i=1 or 2 stands for vulnerability and criticality, while the corner mark j=1,2,… stands for the appropriate index code of the perspectives which are considered.

B. Vulnerability and Criticality Assessment Methods

In this study, each index is classified according to a five-level scale. Based on the relativity of the index value, the vulnerability strength can be described as follows: Rank 1 is defined as very low, Rank 2 is defined as low, Rank 3 is defined as average, Rank 4 is defined as high, and Rank 5 is defined as very high.

The jth ($j = 1,2,\cdots$) index of the ith ($i = 1,2,3$) dimension is $I_{(i,j)}$, which can be converted into Rank $R_{(i,j)}$ based on the definition. The maximum of $R_{(i,j)}$ is defined as max{ $R_{(i,j)}$ }, and the minimum of $R_{(i,j)}$ is defined as min{ $R_{(i,j)}$ }. Therefore, each index is determined by normalization

$$R^*_{(i,j)} = \frac{R_{(i,j)} - \min\{R_{(i,j)}\}}{\max\{R_{(i,j)}\} - \min\{R_{(i,j)}\}} \quad (1)$$

where $R^*_{(i,j)}$ is a standardized or normalized value from zero to one. After calculating and analyzing the impact of each index on vulnerability using the Analytical Hierarchy Process (AHP) method to obtain the weight of each index $w_{(i,j)}$, the impact F_i of the ith dimension of disaster vulnerability is defined as

$$F_i = \sum_{j=1}^{J_i} w_{(i,j)} \times R^*_{(i,j)} \tag{2}$$

where J_i refers to the total index of the ith dimension. After the impact of each dimension on vulnerability has been calculated, analyzed, or performed using AHP to obtain the weight of each index $p_{(i)}$, the overall impact (aggregative index) V on all dimensions of disaster vulnerability is

$$V = \sum_{i=1}^{3} p_{(i)} \times F_{(i)} \tag{3}$$

C. AHP Calculation

AHP calculation is used to classify issues into simple hierarchy levels. The evaluation method is used to determine the priority levels or contributions of each element (factor) in a level, which are integrated into the overall priority level for all programs (factors). The AHP calculation has the following steps [4]:

- Statement of assessment problems: The problem is the basis and focus of the study and the objective of the final assessment stage. Therefore, it should be clearly defined so that the discussion does not deviate from the topic.
- Identification of all factors influencing the decision: Based on previous studies, relative theories, and experience or by means of group brainstorming and the Delphi method, the factors that may influence the decision are listed and separated according to their relative or independent degree.
- Establishment of relationship levels: The relationship levels can be established from top to bottom, generating each level gradually, or from bottom to top starting from the program to objective level. The number of levels depends on the requirements of the actual problem.
- Establishment of paired comparison matrix: The AHP performs a paired comparison of all programs or factors, thus obtaining a Positive Reciprocal Matrix. Thereafter, the eigenvector of this matrix is calculated to obtain the prioritized vector of this level. The relative priority of the final program is obtained by adding all of the prioritized vectors in all levels (namely, factor weights).
- Calculation of the eigenvector, maximal eigenvector, and priority value vector: The priority value vector (weight) must be derived from the paired comparison matrix obtained by the AHP.
- Consistency test: The consistency test evaluates the consistency of the decision maker before and after making judgments and is used in the paired comparison matrix.
- Calculation of overall level weight: After calculating the weights of all level factors, the overall level weight can then be calculated. If the overall level structure passes the consistency test, then the alternative scheme of the final objective can be determined according to the weight number of every alternative scheme.
- Gathering of decision information: When the whole issue is made, the level structuring mentioned in above is used to obtain the relative priority value of each factor for all levels and to pass through the consistency test, the results are provided to the decision makers for their reference in determining relative reliability.

D. Disaster Risk Assessment

Disaster risk assessment requires integrated consideration, including the overall vulnerability and hazard analysis. Other than the reality aspect, the economic, social, and environmental aspects should also be considered in the discussion. The UN Disaster Relief Organization (UNDRO) [5] and National Science and Technology Center for Disaster Reduction (NCDR) [6] proposed an operational definition of disaster risk R :

$$R = H \text{ (Hazard)} \times V \text{ (Vulnerability)}. \tag{4}$$

This equation shows the possible combinations of disaster risk R, disaster potential H, and vulnerability V. Disaster risk refers to the variation degree which may cause disasters. Generally, if disaster strength is strong and frequency is high, then the damages and losses caused by disasters are more severe. The exposure of affected bodies involves all people and properties, such as personnel, livestock, buildings, and crops, among others, that may be threatened by the risk factor. If the exposure of personnel and properties to the risk factor and the value of stricken properties in an area are high, then the potential loss will be significant. Vulnerability refers to the ease with which potential risk factors cause damage or loss to the properties in the given areas. The higher the vulnerability, the larger the losses and the higher the disaster risk [7]. Adaptability refers to the ability of the government and individuals to adopt a series of measures for preventing and reducing risk. The higher adaptability, then the risk is lower.

The assessment of vulnerability and risk in water supply and demand refers to the probability of water shortage, activity level, damage loss, probability of influence and criticality on the economic, social, and natural environment in a certain area during a specific period. A water resource system is complicated because of the mutual combination of natural and artificial structures. A water resource system includes water, storage, transportation, utilization, drainage, among others. The system presents the characteristics of a multi-objective and multi-level structure. Simply put, the system manages the shortage and effects of water resources, and determines the supply and demand of water. Drought and water shortage risk means the occurrence of water supply shortage in the water resource system, the probability of the occurrence of the shortage, and the level of losses arising from the uncertainty of water supply and demand under a specific space-time environment.

The degree of losses caused by the water shortage disaster is the result of the joint influence of natural and artificial factors. The IPCC [8] reports that water vulnerability is an adverse effect of climate change on the system, and a function of the range and change rate within the system, its sensitivity, and adaptability. Vulnerability is closely related to sensitivity. A vulnerable system is unstable and sensitive to the influence or interference of the external climate change. Water vulnerability means the change of the water resource structure; decrease in quantity and reduction in quality of water resources because of climate change and artificial activities; change in water supply, demand, and management; and the degree of occurrence of natural disasters, such as drought and flood [9].

III. Research Scope, Materials Collection, Assessment Result, and Comprehensive Discussion

A. Research Scope and Data Collection

The area of this research is "Taijiang Area," which is located at the southwestern part of Taiwan. This area is a block where the terrain changes dramatically. Before the accretion, the site was an enclosed sea with an area of about 1050 km2 and called "Taijiang Neihai." Several rivers flowed into the territory. In the early times, Taijang Neihai was the center of politics, military, education, and culture. Today, the administrative boundary of Taijiang mainly includes the Tainan area. Fig. 2 shows all the 37 districts of the scope and analysis of the present study.

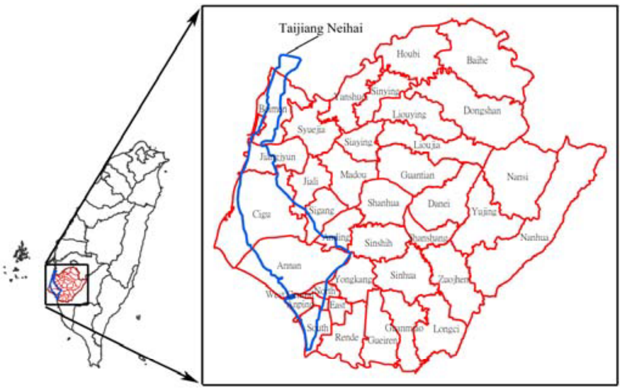


Fig. 2 Administrative boundary of research scope

The materials for this research were collected based on the two levels of vulnerability (exposure and disaster-resistance) and criticality. Every level contains several pointers. Data about the situation of each index for the past 10 years were collected, which in turn were considered as the bases for assessing the vulnerability and risk of water supply and demand. The collected materials are shown in Table I.

TABLE I
BASIC INFORMATION OF DATA COLLECTION

Level		Item	Time (AD)	From
Vulnerability	Exposure	Number of industrial enterprises	2010	Municipal government
		Value of industrial output	2001–2010	Municipal government
		Population density	2001–2010	Municipal government
		Number of people using water	2001–2010	Municipal government
		Agricultural area	2010	Chia-Nan Irrigation Association
	Disaster-resistance	Water consumption per capita per day (domestic water)	-	WRA, MOEA*
		Water consumption per output value (industrial water)	2001–2010	WRA, MOEA*
		Irrigation rate (agricultural water)	-	Chia-Nan Irrigation Association
Criticality		Deficiency ratio of industrial water	2001–2010	WRA, MOEA*
		Deficiency ratio of agricultural water	-	Estimation based on model
		Deficiency ratio of domestic water	-	Estimation based on model
*: WRA, MOEA: Water Resources Agency, Ministry of Economic Affairs				

B. Assessment Result and Comprehensive Discussion

1. Assessment of Weight

In assessing the weight, this research adopts two models, namely, equal and AHP, according to the questionnaires constructed by experts and scholars. The weights of various indexes shown in Fig. 1 are based on the analysis of the "Assessment of Climate Change Impacts on Flood and Drought Disasters" which was implemented by the NCKU Research and Development Foundation under the entrustment of the WRA, MOEA [10]. The weights based on the two assessment models are shown in Table II.

Among the weights of various indexes of criticality, the most important is the deficiency ratio of domestic water, whose weight is up to 0.566. Flooding depth follows with a weight of 0.271. The weight of the deficiency ratio of agricultural water is the smallest, which is only 0.174. In other words, in terms of criticality, the order of the influence of the three water utilization targets is domestic water > industrial water > agricultural water. This ranking is also embodied in the order of vulnerability of pointer weight of the three water utilization targets. In terms of the impact on the seashore disaster risk, the weight of criticality is a little higher than that of vulnerability, that is, 0.508 for the former and 0.492 for the latter.

2. Vulnerability and Criticality Analysis

For vulnerability, every index can be divided into five grades according to their characteristics as shown in Fig. 3. By calculating the various indexes, the vulnerability of water supply and demand is obtained (Fig. 4). Fig. 4(a) is obtained from the calculation based on equal weight, whereas Fig. 4(b) is obtained from the calculation based on AHP weight. According to the classification result based on equal weight, the vulnerability values of Yongkang and East are relatively high. Moreover, the vulnerability of the 12 districts, which include Baihe, Nansi, Zuojhen, Yujing, Nanhua, Danei, Sinshib, Annan, North, West Central, South, and Rende, is intermediate. The vulnerability of the other districts is low. According to the calculation based on AHP weight, the vulnerability results of Yongkang and East are very high. These results are the same as the results based on equal weight. The vulnerability of Annan, North, West Central, Rende, and Nansi is ranked as secondary high, and the vulnerability of Baihe, Danei, Yujing, and South is intermediate. Overall, in the aspect of making vulnerability maps, the classification of vulnerability grades obtained based on AHP weight is mainly affected by three index factors. These factors are number of people using water, water consumption per capita per day and value of industrial output, which all have relatively high sensitivity.

TABLE II
AHP ASSESSMENT ANALYSIS TABLE OF WEIGHT OF WATER SUPPLY AND DEMAND RISK INDEXES

Level		Index	
Name	Weight	Name	Weight
Vulnerability	0.492	Number of industrial enterprises	0.061
		Value of industrial output	0.117
		Population density	0.128
		Number of people using water	0.168
		Agricultural area	0.079
		Water consumption per capita per day	0.204
		Water consumption per output value	0.146
		Water duty	0.097
Criticality	0.508	Deficiency ratio of industrial water	0.260
		Deficiency ratio of agricultural water	0.174
		Deficiency ratio of domestic water	0.566

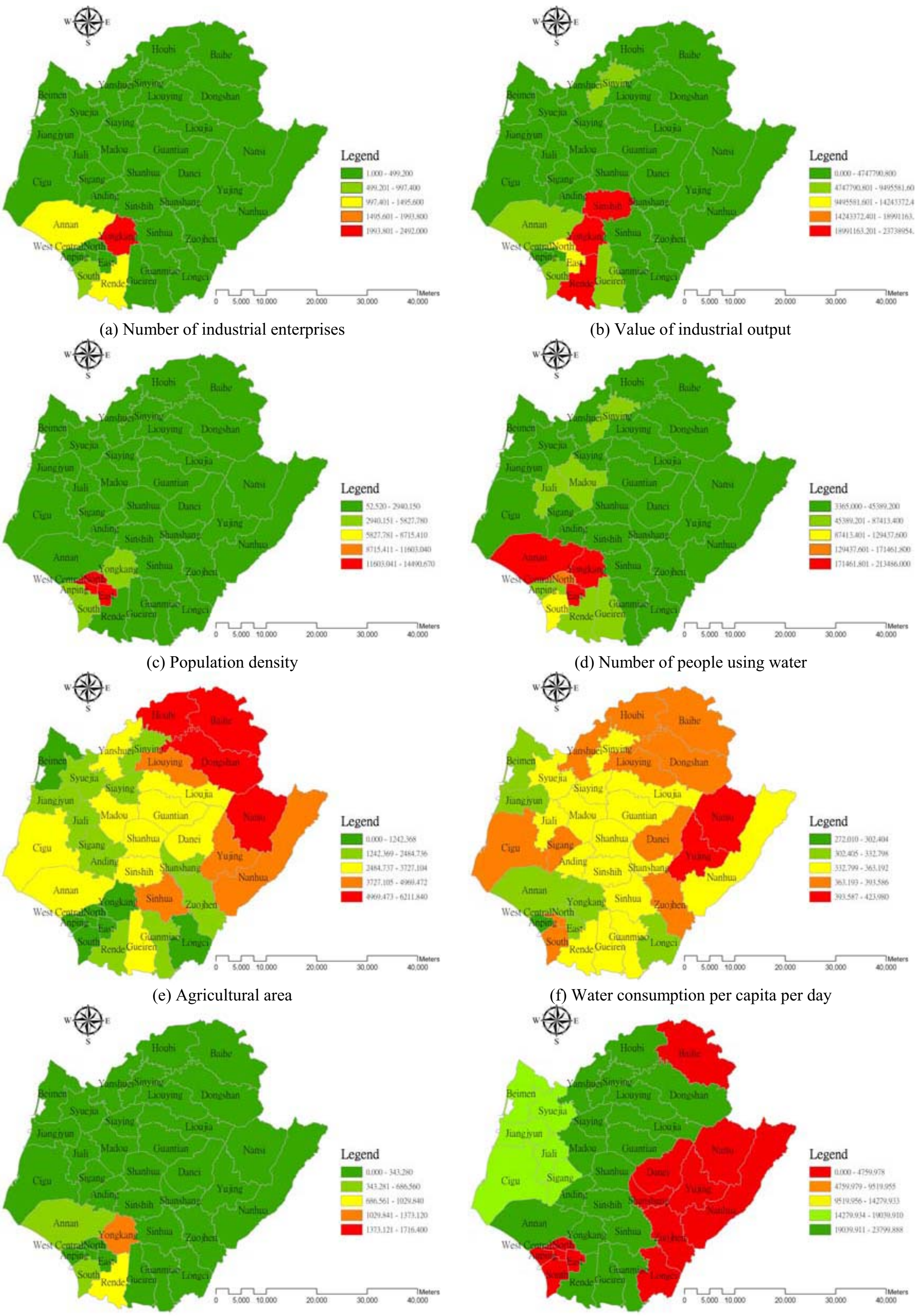
The estimation of the domestic, industrial, and agricultural water consumptions for the target year (2039) considered climate change situations in the future. Hence, this research conducted simulations, analysis, and compared the shortage of domestic, industrial, and agricultural water under different situations. In addition, the shortest situation of water in the simulation event year was sorted. This paper considered two situations. For the first situation, climate condition was set as follows. In the wet season, one time of standard deviation was added, whereas in the dry season, one time of standard deviation was reduced. Impact analysis on the climate condition and the base period was conducted. For the second situation, the climate condition was set as follows. One time of standard deviation was reduced in both wet and dry situations. Impact analysis on the climate condition and the base period was conducted as well. After the development plan for industrial water and tap water facilities is completed, the stimulated deficiency ratio for the target year 2039 was computed (Fig. 5). In this plan, agricultural water consumption does not increase because of the assumption that land irrigation does not expand. After comparing the differences of the deficiency ratios of domestic water in various districts under the two situations, the following results emerged. The water shortage grade of Shanhua in situation one was determined as Grade 1, but in situation two, the water shortage grade was Grade 5. This finding indicates that water shortage disaster is relatively serious. The shortage of industrial and agricultural water under situations one and two are almost the same.

Fig. 6 shows the criticality maps of water consumption of the various targets for the target year, and the results of the analysis. The districts with relatively high criticality that were analyzed based on equal weight are similar to the districts with intermediate and high risk (Grade 5) of the domestic water consumption. In the AHP weight analysis, the increase in the weight of domestic water consumption is highlighted, which shows the influence of domestic water target on criticality is very huge.

3. Risk Analysis and Comprehensive Discussion

Fig. 7 shows the result of the water supply and demand risk map in 2039. According to the analysis based on equal weight, by 2039, the water shortage risk in one district (Yongkang) will reach Grade 4, and no district will reach Grade 5. Yongkang will reach Grade 4 because of the expansion of the Yongkang Sci-Tech Industrial Zone in this district. Hence, the industrial water consumption of 10,000 cubic meters per day increases. According to the result of the analysis based on AHP weight, the water shortage risk in 16 districts will reach Grade 4 or 5, and the degrees of risk in Yongkang and East will be the highest, which will reach up to Grade 5. The increase in grades will take place mainly because of the relatively high population density in such districts, and the relatively large influence of water shortage disaster.

Article 4 of the *Local Government Systems Act* stipulates: “A municipality directly under the jurisdiction of the Central Government shall be set up in the area where the population is more than 1.25 million and there is special need beyond the political, economic, cultural, and metropolitan region development. A city shall be set up in the area where the population is more than 500 thousand but less than 1.25 million, with developed industry and commerce, rich self-government financial resources, convenient transportation and complete public facilities.” Based on this article, cities in Taiwan directly under the jurisdiction of a county, a province, and the Central Government should be called “city,” whereas other places should be “town” [11]. The 37 districts in Tainan, which is the designated area of this research, consist of 6 districts of the former Tainan City and 31 towns of Tainan County. The 6 districts of the former Tainan City can be considered as “city,” whereas the 31 towns of Tainan County can be considered as “towns.” Table III shows the comparison of the urban and rural differences of water supply and demand risk levels in the target year based on the geographical data. The risk differences under the two situations are not big. On the one hand, based on equal weight, the risk level of cities is about 0.5 higher than the grade of the towns. On the other hand, based on AHP weight, the risk level of cities is about one grade higher than the towns. Both methods show that the risk level of cities is higher than towns. Moreover, the risk level of cities based on AHP weight is about 1.8 higher than equal weight. The risk level of towns based on AHP weight is about 1.3 higher than equal weight. The risk level of cities is high. The government generally pays more attention to the adjustment strategy for the cities. Although the risk level of towns is relatively low, the government should also provide proper adjustment strategies for the towns to cope with the risk levels.



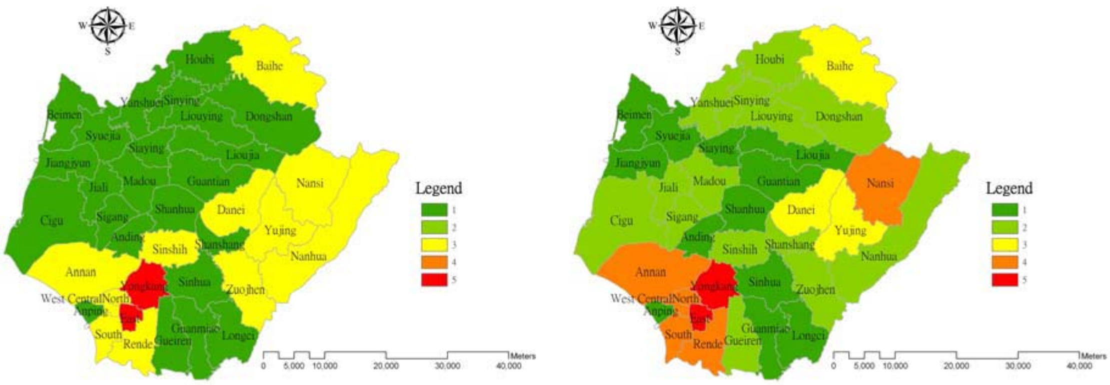
(a) Number of industrial enterprises (b) Value of industrial output

(c) Population density (d) Number of people using water

(e) Agricultural area (f) Water consumption per capita per day

(g) Water consumption per output value (h) Water duty

Fig. 3 Calculation result of the various indexes of the vulnerability of water supply and demand



(a) Equal weight (b) AHP weight

Fig. 4 Vulnerability map of water supply and demand

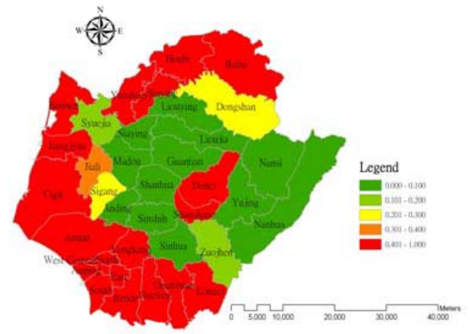
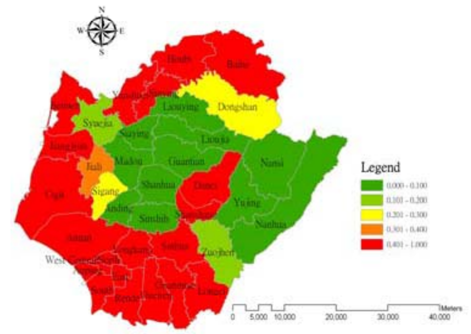
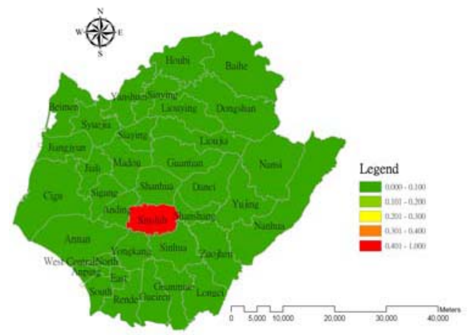
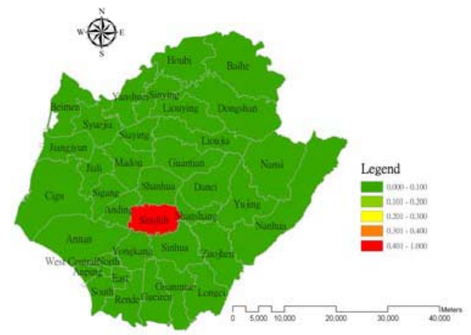
Target of water consumption	Situation 1	Situation 2
Domestic water		
Industrial water		
Agricultural water		

Fig. 5 Distribution of the deficiency ratios of the various water consumption targets in the research area in the target year (2039)

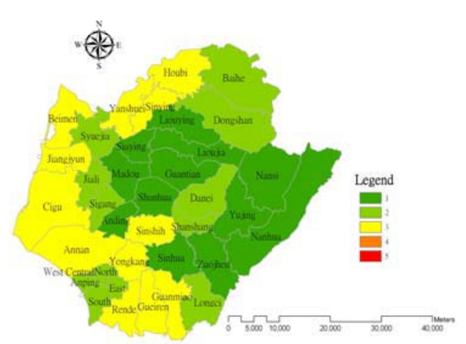
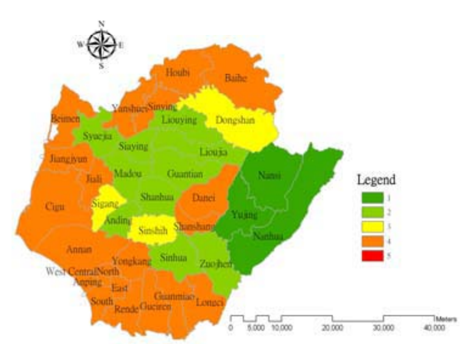
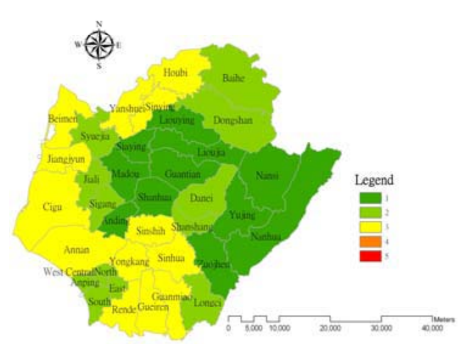
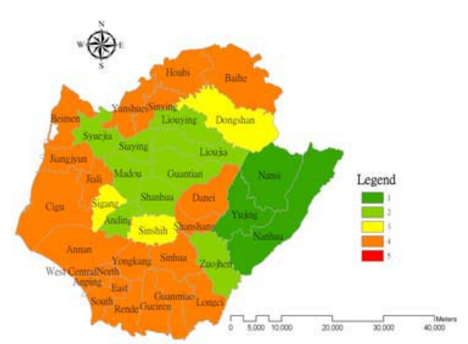
Situation	Equal weight	AHP weight
1		
2		

Fig. 6 Water criticality in the research area for the target year (2039)

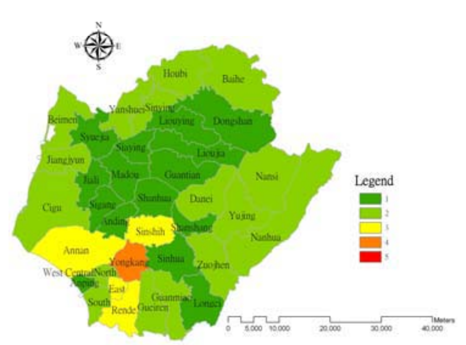
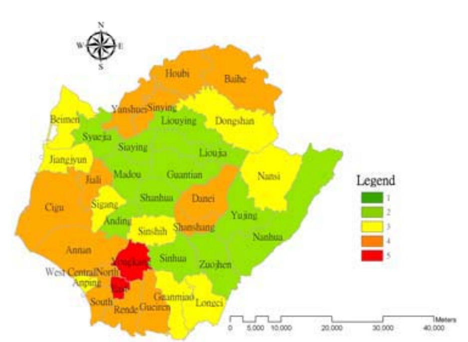
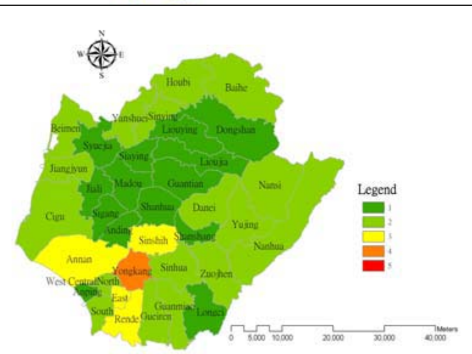
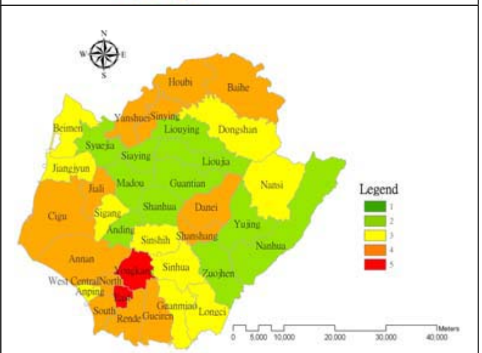
Situation	Equal weight	AHP weight
1		
2		

Fig. 7 Water supply and demand risk map in the research area in target year (2039)

TABLE III
COMPARISON OF THE DIFFERENCES OF WATER SUPPLY AND DEMAND RISK LEVELS IN URBAN AND RURAL AREAS FOR THE TARGET YEAR (2039)

Situation	Statistic	Equal weight		AHP weight	
		Cities	Towns	Cities	Towns
1	Mean	2.17	1.68	4.00	3.00
	Standard deviation	0.69	0.74	0.58	0.92
2	Mean	2.17	1.71	4.00	3.03
	Standard deviation	0.69	0.73	0.58	0.90

IV. CONCLUSION

1. Vulnerability was considered from the two aspects of exposure and disaster-resistance. Based on equal weight, two districts belonged to a very high-grade district (Grade 5), but no district belonged to a high-grade district (Grade 4). According to the result based on AHP weight, two districts belonged to a very high-grade district (Grade 5), but six districts belonged to a high-grade district (Grade 4).
2. In the criticality analysis under the two situations, the result based on equal weight showed that 13 districts belonged to an intermediate-grade district (Grade 3). However, the result based on AHP weight showed that 22 districts belonged to a high-grade district (Grade 4), which accounted for about 60% of all the districts. These results showed that the impact of criticality on the districts and the change it brought to the districts were relatively big.
3. The risk analysis result based on equal weight showed that one district belonged to a high-grade district (Grade 4). The risk analysis result based on AHP weight showed that 16 districts belonged to a high-grade or higher-grade district (Grade 4 and Grade 5), and two districts reached the highest grade, Grade 5.
4. The water supply and demand risk level analysis in the research area showed that the risk level in cities was higher than that in towns. The risk level in cities was high because the government generally paid more attention to their adjustment strategy. Furthermore, although the risk level in towns was relatively low, the government should also provide proper adjustment strategy for them to cope with the risk levels.

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