An Evaluation Indicator of Rainwater Harvesting Systems in Northern Taiwan

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Abstract

Rainwater harvesting systems have been widely accepted as solutions to alleviate the problems of water shortages. The main purpose of this study is to establish a rainwater utilization indicator system to analyze regional rainfall characteristics, and to extract representative variables and weights, as well as develop a formula for an indicator. Then, acquired scores will show the potentials for discrepancies between different rainwater harvesting systems. This study has also compared the scores and long-term simulated water-savings percentages and constructed an effectiveness evaluation formula for rainwater harvesting systems. Eventually, according to the score range, the potentials have been clustered for the establishment of rainwater harvesting systems. Through this indicator system, weight in the scoring formula indicates the inter-relationship of the variables of a rainwater harvesting system and designers can review the system's design to adjust the parameters for the optimal system. For future reference, the clustering of rainwater utilization potential reflects the potential for the establishment of rainwater harvesting systems in different districts. The proposed rainwater indicator system should be used for reviewing proposals and according to the potential, an optimal design and regulations can be chosen for the most suitable utilization and peak effectiveness of a rainwater harvesting system.

Keywords: rainwater harvesting system; rainwater utilization indicator; principal component analysis; cluster analysis of potentials

1. Introduction

Along with the rapid growth in global population comes a challenge for countries all around the world - how to acquire an adequate supply of potable water. For those areas having plentiful rainfall, the rainwater harvesting system had been adopted as a common solution (Ghisi et al., 2007; Herrmann and Schmida, 2000). In Sweden, analysis carried out on a rainwater collection system for domestic water supply revealed that a significant measure of potable water can be saved if rainwater tanks are included as part of a dual water supply solution (Villarreal and Dixon, 2005). In Brazil, a study indicated that the potential for using rainwater for saving potable water in residential sectors situated in varied geographic regions ranged from 48% to 100% (Ghisi, 2006). In the UK, a study revealed that the average water saving efficiency because of the use of rainwater for toilet flushing was approximately 57% (Fewkes, 1999a). In Taiwan, 32% of potable water used in the residential sector could be replaced by rainwater, mostly for toilet flushing, cleaning, and gardening (Cheng et al., 2006).

Most of Taiwan receives abundant rainfall throughout the year. In northern Taiwan, the average annual rainfall is about 2,500 mm (WRA, 2001). If rainwater can replace the original use of potable water for the above mentioned functions, this would alleviate water problems and save money on potable water consumption. Furthermore, it could also help to reduce runoff water and prevent urban floods, which have occurred in recent years. Consequently, rainwater harvesting systems have been recommended for adoption and to be linked to the water resources indicator of the Taiwan green building evaluation system (ABRI, 2007).

Hitherto, the rules for water resources indicators merely stipulated the storage tank size based on the rainfall probability and rainwater demand. There were not effective tools to evaluate the performance of a rainwater harvesting system. Designers were required to collect a huge amount of rainfall data in order to simulate the complicated process before developing a reasonable system and evaluating its effectiveness, and it was difficult to design an optimal system due to lacks of weights for relevant variables. Moreover, the distinct...
potentials of rainwater harvesting systems in each district could not be presented and compared due to lack of an estimation criterion. Accordingly, this study proposes to establish an objective, comprehensive, but simple evaluation indicator to simplify the design process. It is integrated with relevant variables to be weighted differently according to levels of impact. The resultant score will indicate any discrepancies in the effectiveness of different rainwater harvesting systems and reflect the potential for potable water savings in different districts. It will also serve as an effective reference in decision making and design for optimized effectiveness.

Compared with complicated processes in the past, this proposed system simplifies the procedures but allows for the preservation of information, and adds calculation convenience and accuracy to rainwater harvesting and utilization design. The rainwater evaluation indicator system developed in this study will help designers simply evaluate the efficiency of an intended rainwater harvesting system by means of the acquired scores along with the effectiveness evaluation model. The analysis of weights will contribute to comprehending the composition of relevant variables, and designers can adjust the design parameters for a system's optimization. Meanwhile, the rainwater utilization potential of each district shows the relationship between rainfall characteristics and system designs which will provide references for the establishment of a district system design.

2. Objective
The main purposes of this study are to establish a rainwater utilization indicator system to analyze regional rainfall characteristics, and to extract representative variables and weights, as well as develop a formula for an indicator. Then, acquired scores will show the potential for discrepancies between different rainwater harvesting systems. The comparison between the scores and water-savings percentages will help to build an effectiveness evaluation model with reference to decision making.

3. Methodology
In general, the effectiveness of a rainwater harvesting system is mainly influenced by these key factors: rainfall characteristics of the district and the system design. In order to accomplish the objective specified above, this study assumed a case as the criterion sample and used historical rainfall data to calculate the score of each district in the sample area. The acquired scores were then used to determine the system's potential and the water-savings percentage evaluation model. In addition, all districts' rainwater utilization potentials were classified into groups in accordance with the scores. A principal component analysis was adopted to construct the rainwater utilization factorial weight and influential coefficient. The representative variables and their weights were extracted to acquire one score. According to the score values, the K-Means method of cluster analysis was adopted to classify rainwater utilization potential. Computer software SPSS13.0 was used for the simulations in this study. Fig.1 shows the research flow chart.

3.1 Sample area
This study investigated a sample area in northern Taiwan. The total sample area is 7,347.23 square meters including 69 districts in Keelung City, Taipei County and City, Taoyuan County, Hsinchu County, and Yilan County as shown in Fig.2. This sample area is in a sub-tropical ocean monsoon climate with an average annual rainfall of 2,500mm. Due to the influence of the northeastern monsoons and its geographical location, precipitation is concentrated on the windward side and in the mountainous areas. Therefore, the coastal areas in the west have less rainfall.
3.2 Rainfall data
The rainfall data were obtained from WRA (2004). The rainfall data ranged over a period of 40 years, from the 1st January 1963 to the 31st December 2002, and the sampling interval was set up as daily precipitation. Missing data in this period were assumed to be zero.

3.3 Simulation of rainwater harvesting and utilization
3.1.1 The criterion sample
A report revealed that with respect to residential buildings in Taiwan, five-floor terrace apartment buildings accounted for the highest percentage, that is, 45.07%; and these buildings averaged 119.1 m² per floor and four people per household (DGBAS, 2000). This study, thus, suggested the use of this criterion sample. Therefore, in the rainwater harvesting and utilization simulation, it was assumed that the criterion sample is a five-floor apartment building with 20 users.

3.3.2 Roof collection area (A)
The roof collection area in this study was defined as the total horizontal area used for rainwater collection and here the vertical area was left out, temporarily. The roof collection area was assumed to be 119.1 m² following the survey result.

3.3.3 Substitute rate
Statistics showed that the daily potable water demand was estimated to be 0.25 m³ per user (Cheng, 2003), therefore, that of the criterion sample was 5.0 m³, of which 32% can be replaced by collected rainwater at most. For the purpose of simulation this study used 32%, 16%, and 8% substitution rates.

3.3.4 Storage multiplier (M)
The capacity of a rainwater storage tank was assumed to be the product of the daily substitute water demand and a storage multiplier (M). This study assumed 10.0, 5.0, and 1.0 as storage multipliers in the simulation.

3.3.5 Water-savings percentage (WSP)
The water-savings percentage refers to the long-term effectiveness of the rainwater harvesting systems. Based on the criterion sample above, a long-term simulation was conducted on the different districts in the sample area. The time for simulation was the same as above, over a period of 40 years, from 1st January 1963 to 31st December 2002. The interval was set up as a daily model. Missing data in this period were assumed to be zero. Formula (1) shows the calculation of water-savings percentage.

\[ WSP = \frac{RS}{WD} \times 100 \% \]  

Where \( WSP \) is the water-savings percentage (%), \( RS \) is the total amount of rainwater use for the 40-year period (m³), and \( WD \) is the total potable water demand for those same 40 years (m³).

3.4 Principal component analysis
The concept of a principal component analysis, based on the relationship of simplified variables, constructs comprehensive indicators for different measurement units and converts variables into scores (Coombes and Wong, 1994). The method is to convert several independent variables into new components with a linear composition in which the correlation coefficients are zero. The feature is the maximum variance among the components, which allows for the existence of maximum differences and the preservation of information.

3.4.1 Variables
Variables that affect the effectiveness of a rainwater harvesting system can be categorized into two dimensions: a regional rainfall characteristic and a system design. In terms of regional rainfall characteristics, intensity and duration are two key factors, \( R \), the average annual rainfall, and \( P \), rainfall probability of a district over the 40-year period (1963-2002) referred to intensity and duration respectively. Variables of a system design include: the collection area, storage capacity, water demands, and amount of rainfall. There is an interrelationship among the above variables. This study proposes to use the combinations of collection areas, storage capacities, demands and rainfall which are expressed in terms of two dimensionless ratios, namely the demand fraction (\( D \)) and storage fraction (\( S \)).

The demand fraction is given by, \( \frac{D}{AR} \), where \( D \) is the annual demand (m³), \( A \) the collection area (m²) and \( R \) is the average annual rainfall (m). The storage fraction is given by, \( \frac{S}{AR} \), where \( S \) is the storage capacity (m³) (Fewkes, 1999b; Fewkes and Butler, 2000).

3.4.2 Standardization
In the process of a principal component analysis, the values of each variable were standardized first to eliminate the influence of different data units. Formula (2) shows the calculation of standardization.

\[ Z_{ij} = \frac{X_{ij} - \bar{X}}{S_i} \]  

Where \( Z_{ij} \) is the standardized value of the observation \( j \) in indicator, \( i \), \( X_{ij} \) is the observation \( j \) in indicator, \( i \), \( \bar{X} \) is the average number of indicator, \( i \), and \( S_i \) is the standard deviation.

3.4.3 Calculation of scores
This study assumed that the principal component was composed of variables and was the linear composition of the standardized values of those variables. Scores were calculated as shown in formula (3).

\[ Y_i = a_{i1}X_1 + a_{i2}X_2 + a_{i3}X_3 + \ldots + a_{ip}X_p \]  

\[ i = 1, 2, \ldots, p \]

Where \( Y_i \) is the score of the principal component, \( a_{ip} \) is the standardized value of the observation \( p \) in indicator, \( i \), and \( X_i \) is the weight.
The principal component analysis distributes important variables to bigger weight values and less important ones to smaller weight values in order to generate the maximum eigenvalue. The corresponding eigenvalue was used for the explanation of the variable deviations.

3.4.4 Test of index

The suitability of a principal component analysis was evaluated by KMO (Kaiser-Meyer-Olkin) test and Bartlett's test. The bigger the KMO value, the more co-factors there are among the variables and it is therefore, more suitable to utilize a principal component analysis. Bartlett's test was used to evaluate the correlation coefficient matrix of variables, and a significance level (α=0.05) was introduced to test the feasibility of a principal component analysis.

3.5 K-Means clustering method

Scores acquired from a principal component analysis refer to the potential of rainwater harvesting systems. In accordance with the score values, K-Means cluster analysis was introduced to cluster scores into high, mid and low potential groups. In the process of cluster analysis, distance was applied to measure the similarity among variables. The distance of all variables from the median point determines their cluster classification. The K-Means method is to compare the Euclidean distance of two points in the P-dimension shown in formula (4). 

\[ D_{ij}^2 = \left( \sum_{k=1}^{P} (X_{ik} - X_{jk})^2 \right)^{1/2} \]  

Where \( D_{ij} \) is the distance from \( i \) to \( j \); \( X_{ik} \) and \( X_{jk} \) are two values of \( i \) and \( j \) in \( K \)-dimension.

4. A principal Component Analysis Of Rainwater Harvesting Systems

4.1 Variable Selection

In the process of variable value standardization, if there is an equal ratio relationship among variables, multi-collinearity exists and therefore, one’s standardized value is able to represent others. In the variables adopted by this study, the \( S \) value (storage capacity) of \( S_i \) (storage fraction, \( S/AR \)) was the \( D \) value (annual demand) of \( D_i \) (demand fraction, \( D/AR \)) times a certain ratio. As a result, there was an equal ratio relationship between \( S_i \) and \( D_i \), and the \( S_i \) standardized value was used as representative. Eventually, the standardized values of \( R \) (average annual rainfall), \( P \) (rainfall probability), and \( S_i \) (storage fraction) were selected as representative in this study.

4.2 Standardized variables

All variables needed to be standardized via formula (2) in the process of a principal component analysis. This study used regression formulae to determine the relationship between variables and standardized values. Formulas (5), (6), (7) show the regression formula of \( R \), \( P \), \( S \).

\[ R' = 1.3150 \times R - 3.2872 \]  

Where \( R' \) is the standardized value of \( R \); \( R \) is the average annual rainfall (m).

\[ P' = 11.453 \times P - 4.5641 \]  

Where \( P' \) is the standardized value of \( P \); \( P \) is the rainfall probability.

\[ S' = \frac{707.2}{M} \times S_i - 4.0925 \]  

Where \( S' \) is the standardized value of \( S_i \), \( M \) is the storage multiplier, and \( S_i \) is the storage fraction.

4.3 Principal components

Table 1. shows the result of a principal component analysis, and through the process of extraction, variables were integrated into three components. In a principal component analysis, an eigenvalue larger than 1.0 is an effective explanation and among the three components, only the eigenvalue of Component 1 reached 2.735, and also the variance explained was 91.167%. The eigenvalues of the other components were far smaller than that of Component 1. Therefore, this study suggests using the principal component analysis result of Component 1 and eliminating that of Components 2 and 3. In accordance with component features and functions, Component 1 was named the rainwater utilization indicator.

4.4 KMO test and Bartlett's test

Table 2. shows the results of a KMO test and a Bartlett's test, where KMO test value reached 0.702. Its principal component suitability ratings lay in the middling to meritorious range. In terms of Bartlett's test, the significance level was proved to be less than 0.05, which means that the generated scores can present the deviations among variables, and there are effective explanations for the result of a principal component analysis.

4.5 Scores

According to results of the component score coefficient, the score of Component 1 is acquired from formula (8) as follows:

\[ SCORE_1 = 0.904 \times R' + (-0.830) \times P' + (-0.680) \times S' \]  

Where \( SCORE_1 \) is the score of Component 1, \( R' \) is the standardized value of \( R \), \( P' \) is the standardized value of \( P \), and \( S' \) is the standardized value of \( S \).

Formula (8) shows the inter-relationship and weight of variables on rainwater harvesting system effectiveness. The scores refer to the eigenvector generated by influential variables after a principal component analysis. The eigenvector indicates the difference of effectiveness between rainwater utilization systems and according to the above statement, the variance explained reaches 91.167%. Table 3. displays the scores calculated by using formula (8) and ranges from 3.0447 to -1.7571.
5. Evaluation and Cluster Analysis of Potentials

5.1 Evaluation of water-savings percentage

According to the principal component analysis, each district has one score - the eigenvalue of the rainwater harvesting system effectiveness. That eigenvalue was compared with long-term water-savings percentage obtained from the 40-year simulation to yield a formula. The score of principal component analysis is reflected by the axis of water-savings vectors for the evaluation of system effectiveness. Due to the different conditions of systems, evaluation and accuracy are affected. The storage capacity of rainwater tanks and substitute water demands are discussed as follows, in order to address the impact on the evaluation formula.

5.1.1 Influence of the storage capacity

Fig. 3. shows the correlation between water-savings percentage and the score of the rainwater utilization indicator if the storage multiplier is set at 1.0, 5.0, 10.0, and the substitute rate is set at 32%. Fig. 3. indicates that the larger the tank's volume, the bigger the slope and intercept to be found in the evaluation formula, and also the $R^2$ value increases. That is to say, that, when the rainwater tank is bigger, a higher level of accuracy is acquired from the evaluation formula. This is because during a typhoon or storm, larger-sized rainwater tanks are able to collect more rainwater while overflows occur in the smaller sized ones due to space limitations, thus, more complexity will be added to the evaluation.

5.1.2 Influence of substitute water demands

Fig. 4. shows the correlation between the water-savings percentage and the scores of the rainwater utilization indicator if the storage multiplier is set at 5.0, and the substitute rate is set at 8%, 16%, 32%. Fig. 4. indicates that when the substitute rate is too low, most collected rainwater cannot be utilized and will overflow. When there is a failure to provide sufficient substitute water, the water-savings percentage will
be reduced. The evaluation formula also shows a low relevance due to overflowing. On the contrary, if the substitute rate is higher, most collected rainwater will be utilized as substitute water and in addition to higher water-savings percentage, the accuracy of the evaluation formula is enhanced.

5.2 Cluster analysis of potentials

Fig.5. and Fig.6. show spatial distribution maps of the average annual rainfall and rainfall probability for the sample area. Apparently, due to the influence of monsoons and the central mountain area, the rainfall distribution becomes less dense gradually from northeast to west. On the windward side, the northeast, the highest average annual rainfall reaches 4,800mm. In the coastal area, on the west, the average annual rainfall is approximately 1,600mm. The spatial distribution of rainfall probability also reflects this situation and on the windward side, the northeastern area, rainfall probability reaches 0.56 and is reduced to 0.27 for the coastal area on the west.

Fig.7. shows the clustering results according to the scores of rainwater utilization indicator and the K-Means method. The high potential is located on the northeastern side, scoring within the range of 3.0447 to 1.5730. The low potential is distributed on the western coastal area within the scoring range of -0.3410 to -1.7571, with the rest being in the mid range. Compared to Fig.5. and 6., Fig.7. integrates the intensity and duration of the regional rainfall, and demonstrates the establishment potential of a rainwater harvesting system in spatial distribution with the results corresponding to the above analysis. Fig.8. reflects a clustering result from the formula of scoring and water-savings percentage and indicates the scoring distribution of potential clustering.
6. Conclusions

Aimed at optimal designs for the effectiveness of rainwater harvesting systems, this study constructed an evaluation indicator system and adopted a principal component analysis to analyze the influential factors of rainwater harvesting system design. Acquired scores show the differences between the effectiveness of rainwater harvesting systems. This study also compared the scores and long-term simulated water-savings percentages and constructed an effectiveness evaluation formula for rainwater harvesting systems. Eventually, according to the score range, the potential was clustered for the establishment of a rainwater harvesting system.

Through extraction, the eigenvalue of Component 1 reached 2.735 and the variance explained was 91.167%. The KMO test value lay in the middling to meritorious range, and the Bartlett's test significance level was less than 0.05. The analysis resulting from the above facts proved that the scores of the extracted components acquired from the indication formula gave a highly effective explanation for the effectiveness of the rainwater harvesting system and showed the differences between systems. This study also named a rainwater utilization indicator according to the property and function of composition.

This study compared the indicator system and long-term water savings percentages to establish an effectiveness evaluation formula. When the utilization rate of the collected rainwater is high, this indicator system has high accuracy and reliability, but, when there is a high overflow rate of collected rainwater, there is a low relevance. This study also classified the scores of the indicator system and compared them with the average annual rainfall and rainfall probability. The clustering result integrates the factors of a region's rainfall: intensity and duration indicating the potential for the establishment of a rainwater harvesting system in spatial distribution.

Through this indicator system, the large quantities of data and high complexity which were requirements in the past can be reduced, and the design procedure simplified for a quick effectiveness evaluation of the rainwater harvesting systems. Weight in the scoring formula indicates the inter-relationship of the variables of a rainwater harvesting system and designers can review the system's design to adjust the parameters for the optimal system. For future reference, the clustering of rainwater utilization potential reflects the potential for the establishment of rainwater harvesting systems in different districts. Districts with low potentials should make improvements to promote effectiveness in utilizing the system design parameters. The established rainwater indicator system should be used for reviewing proposals and according to the potential, the optimal design and regulations should be chosen for the most suitable utilization and peak effectiveness of a rainwater harvesting system.
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