Two-dimensional Fuzzy Statistical Analysis Application in Urban Reclaimed Water Target Selection

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Abstract

Taiwan faced a severe water shortage in 2020 and 2021. Industrial water demand has continued to rise and, despite the additional water-saving practices used by industry, other water demands, including agricultural and urban uses, have encountered similar water shortage crises. This study employs two-dimensional fuzzy statistics and analysis as a way to accurately represent the inclination, attitudes, and thinking patterns of human beings. A sample questionnaire survey was conducted on Kaohsiung residents. As part of this study, a total of 273 questionnaires were distributed; 245 valid samples were collected and, after invalid responses were removed, the valid response rate was 89.4%. Data analysis demonstrated that, when evaluating reclaimed water programs, the public attaches the most importance to water safety, followed by a stable water supply. In terms of uses for reclaimed water, the public finds it appropriate to direct reclaimed water to agriculture use first, followed by industrial use. In case of a water shortage, people find it necessary to control domestic water use, and the water control scheme they find acceptable is the "1-day supply and 1-day suspension." When reclaimed water use is necessary under a water control program, people find that NTD 15-20 is the most acceptable pricing plan.

1. Introduction

Despite the annual rainfall in Taiwan being 2.5 times that of the world's average rainfall, regional water shortages still occur frequently in Taiwan due to the extremely uneven distribution of rainfall in terms of time and space. During gradual and severe water shortage crises, the government has proposed strategies to stabilize the water supply by increasing resources, saving water, scheduling water, and storing backup water. The goal of saving water is to increase the overall water recovery rate of factories from 70% to 80% by 2031 and to promote six reclaimed water plant demonstration projects to show the government's emphasis and determination regarding water regeneration.

However, although reclaimed water has been promoted in Taiwan for a long time, its use has not been yet been expanded. Taiwan continues to encounter challenges in the technical, economic, and consumption aspects related to water. The environment for promotion in Taiwan is different compared to that of other countries or regions, and the concept of water resources is not valued by society. This is a serious problem that requires detailed discussions.

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This study analyzed the international use of reclaimed water based on an analysis of Taiwan's water resources in order to understand the Taiwanese people's acceptance of reclaimed water. In the near future, the results can be used by the government to understand the importance attached to reclaimed water, the public's acceptance of using reclaimed water for other purposes, and the public's views on the use of reclaimed water to make up for the lack of water, due to the government's proposed rationing measures. This study also makes recommendations on acceptable reclaimed water prices.

2. Review of the Water Resources in Taiwan

Taiwan is surrounded by the sea, and the climate is warm and humid. May to June is "plum rain" season. There are typhoons in summer and northeast monsoons in winter, all of which bring considerable rainfall to Taiwan. According to statistics, the average annual rainfall in Taiwan can reach 2,500 mm, which is approximately 2.6 times that of the world's average. Due to uneven rainfall distribution in terms of time and space, topographical conditions, and extreme climate changes, however, the annual rainfall per person is only approximately 4,000 cubic meters, less than one-fifth of the world's average of 21,796 cubic meters.[1)]

Taiwan is not immune to global climate change and extreme climate impacts. Taiwan experienced the largest drought in 67 years in the first half of 2015, and the second lowest winter rainfall in 70 years in the spring of 2017. The lack of landed typhoons and the scarcity of rain in 2020 plunged Taiwan into the worst drought in 56 years. Many reservoirs held less than 20% of their capacity, with some having water levels below 10%. An alert was triggered in Taichung and Miaoli in April 2021, when the water-rationing measures of the 5-day supply and 2-day suspension were implemented. This caused the warning lights to go on in many areas of Taiwan. It also increased the difficulty of water utilization and dispatch in Taiwan.[2)]

The low price of tap water has an adverse effect on water resources in Taiwan. There has been no increase in water prices since the adjustment of water price by the Taiwan Water Corporation in July 1994. The average price of NTD 10 has remained the same for more than 24 years. In other countries, water price per cubic meter is NTD 46 in Japan, NTD 38 in Germany, NTD 24 in Australia, and NTD 20 in Singapore. Taiwan's low water tariffs have led to the habit of waste, and the current differentiated water prices for different water consumption are not obvious. The price of high water consumption does not influence the user's choices. Although people are aware of water conservation, the actual implementation needs to be improved. There is no economic incentive for industrial investment in water-saving equipment, which is unfavorable to improving water use efficiency.[3)]

In order to stabilize the society and meet the needs of sustainable economic development, domestic water resources must be provided through diversified water supply methods to meet the water needs of everyone. On the one hand, water conservancy-related units should continue to develop traditional water resources, such as reservoirs, barrages, and groundwater. On the other hand, they should also actively evaluate the development of new water sources, such as rainwater storage, undercurrent water utilization, reclaimed water utilization, and seawater desalination. The reclaimed water mainly comes from the recycling of discharged water from public sewage treatment plants, which is more stable in water quality and quantity than other water sources, and is one of the current priorities for the development of

emerging water resources.

The Legislative Yuan, the highest legislative organ of Taiwan, passed the "Reclaimed Water Resources Development Act" in 2015. According to the definition of reclaimed water in the regulations, reclaimed water refers to the sewage water or discharged water that can be reused after treatment. The Executive Yuan, the highest administrative organ of Taiwan, approved "Demonstration and Promotion Plan for the Recycling and Reuse of Discharged Water from Public Sewage Treatment Plants" in 2013, with total funding of NTD 15.2 billion for an eight-year period, including six demonstration projects at the Fengyuan Plant and Futian Plant in Taichung, the Anping Plant and Yongkang Plant in Tainan, the Fengshan River Plant, and the Linhai Plant in Kaohsiung, four of which are in the south.[4] The water supply schedule is shown in Table 1 and the water supply quantity is as follows:

(1) Anping Plant: In 2022, it will supply 37,500 tons of water daily.
(2) Yongkang Plant: In 2021, the daily water supply will be 9,000 tons, and it will increased to 37,500 tons in 2023.
(3) Fengshan River Plant: It has been supplying 45,000 tons of daily water since 2019.
(4) Linhai Plant: The daily water supply was 33,000 tons of water in 2021.

Table 1 Reuse of Discharged Water from Public Sewage Treatment Plants in Southern Taiwan

Area	Sewage treatment plant	Target industrial zone for water supply
Tainan	Liuyin	Tainan Eco-industrial Park
	Anping	Tainan Branch of Southern Taiwan Science Park, Anping
	Yongkang	Tainan Branch and Shugu Branch of Southern Taiwan Science Park
	An-nan	Tainan Technology Industrial Park
	Rende	Bao-an
Kaohsiung	Fengshan River	Linhai, Dafa
	Linhai	Linhai
	Nanzi	Nanzi Branch of Export Processing Zone, Dashe
	Luchu	Kaohsiung Branch of Southern Taiwan Science Park
	Linyuan	Linyuan
Pingtung	Liukuaicu	Pingtung Branch of Export Processing Zone, Pingtung

3. Research Method—Fuzzy Statistical Analysis

Human thinking mainly comes from the cognitive consciousness of natural and social phenomena. However, the language of human knowledge has fuzziness due to its own subjective consciousness, time, environment, and different angles of analyzing things. Thus, Wu (2005) proposed that fuzziness theory refers to the fuzzy measure and classification principle used by the human thinking mode to give a more stable description mode in handling multivariate, complex, ambiguous, and uncertain phenomena.[5]

Traditional questionnaires often require respondents to fill in a single value in the questionnaire options. However, as human feelings for questionnaire items are fuzzy and uncertain, the traditional questionnaire cannot truly represent the respondents' feelings. Nevertheless, if respondents can express their true preference for questions by using

membership function or interval values according to their own consciousness, they can convey the true thinking of human beings more completely.

Membership function is a concept of the fuzzy theory derived from the characteristic function in traditional sets. It is used to express the membership grade of elements to fuzzy sets, and its range is between 0 and 1. In the fuzzy set theory, Zadeh (1965) mentioned that if a certain element belongs to a certain set to a greater extent, its membership value is closer to 1; otherwise, it is closer to 0.[6)]

Traditionally, when defining whether a person is "middle-aged," we often use 45 years old as a boundary. However, is a 40-year-old or a 55-year-old man not considered "middle-aged" ? A more reasonable answer can be obtained when the membership function is used. If the age of 45 absolutely belongs to "middle age," its membership grade naturally belongs to 1, while the membership function value of age 40 is 0.8, which means that a 40-year-old belongs to "middle age" with a 0.8 membership function value. Meanwhile, the membership function value of age 55 is 0.3, which means that a 55 year old belongs to "middle age" with a 0.3 membership function value. Compared with the characteristic function of the traditional set, the membership function smoothens the characteristic function, as shown in Figure 1.

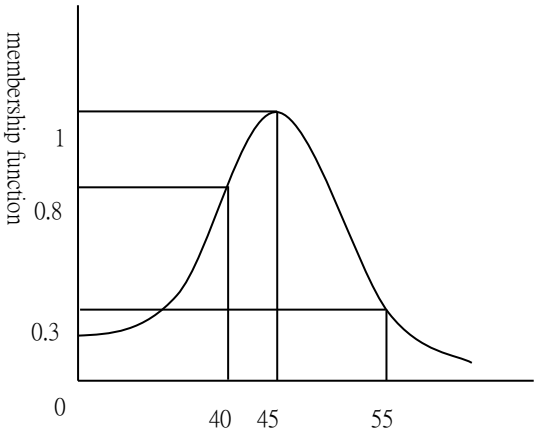

Figure 1. Membership Function for "Middle Age"

The expression of the function definition can refer to the relationship between the elements of an infinite fuzzy set and their membership grade or the relationship between elements of a finite fuzzy set and their membership grade. When considering the items with fuzzy characteristics, the data itself has uncertainty and fuzziness.[7)]

This study is about the public acceptance of urban reclaimed water, and the fuzzy number can be defined as follows:

U is set as a domain of discourse, and $\{L_1, L_2, ..., L_n\}$ is the factor set of U. u is the real number function between the range of [0, 1]; that is, $u : U \rightarrow [0,1]$. If the membership function of a sentence X distributed in the domain U with respect to the set of factors is expressed as $\{\mu_1(X), \mu_2(X), ..., \mu_n(X)\}$, then in the case of discrete, the fuzzy number of the sentence X can be expressed as:

$$\mu_U(X) = \frac{\mu_1(X)}{L_1} + \frac{\mu_2(X)}{L_2} + ... + \frac{\mu_n(X)}{L_n}$$

The design is as follows, according to the definition of the two-dimensional fuzzy number.

Assuming that public acceptance is as follows, there are m factors (factor, F) that consider the choice of n assessment item (B). If the two-dimensional fuzzy statistics of water is used, the domain of discourse is U={Bi, i=1, 2,..., n}, V={Fj, j=1, 2,..., m}, X= weighted grade of the assessment item, and is represented by u (X); Y= the acceptance of the water use target and is expressed in u (Y). In filling out the questionnaire, the numbers between 0 and 1 for the weighted grade of U must be filled in, representing this assessment item's "weighted grade." In addition, the numbers between 0 and 1 for the grade of V must be filled in, representing the "acceptance grade of water use targets." Then, the two-dimensional fuzzy number matrix of public acceptance is:

An example of one questionnaire:

The membership grade of water quality, stable supply, reasonable price, and reclaimed water technology is 0.3, 0.4, 0.1, and 0.2, respectively. Under the acceptance weight grade of water quality (0.3), the membership grade of industrial water, agricultural water, environmental protection water, and miscellaneous water is 0.1, 0.5, 0.3, and 0.1, respectively. The two-dimensional fuzzy sample matrix is obtained as:

$$\begin{bmatrix} (0.1,0.3) & (0.1,0.4) & (0.5,0.1) & (0.1,0.2) \\ (0.5,0.3) & (0.5,0.4) & (0.2,0.1) & (0.4,0.2) \\ (0.3,0.3) & (0.3,0.4) & (0.2,0.1) & (0.4,0.2) \\ (0.1,0.3) & (0.1,0.4) & (0.1,0.1) & (0.1,0.2) \end{bmatrix}$$

4. Discussion on Urban Reclaimed Water Target Selection

In this study, a total of 273 questionnaires were distributed; 245 valid samples were collected and, after invalid responses were removed, the valid response rate was 89.4%. Firstly, the fuzzy statistics of each questionnaire item obtained according to the 245 samples data are as follows:

(1) Fuzzy expected value matrix

$$\overline{S1} = \begin{bmatrix} (0.215,0.416) & (0.304,0.204) & (0.291,0.183) & (0.326,0.197) \\ (0.338,0.416) & (0.306,0.204) & (0.297,0.183) & (0.279,0.197) \\ (0.291,0.416) & (0.231,0.204) & (0.233,0.183) & (0.224,0.197) \\ (0.172,0.416) & (0.159,0.204) & (0.178,0.183) & (0.181,0.197) \end{bmatrix}$$

Among $\overline{S1}$, 0.416, 0.206, 0.183, and 0.197 is the expected membership grade of assessment item safe quality, stable supply, reasonable price, and reclaimed water technology, respectively.

Moreover, 0.215, 0.338, 0.291, and 0.172 is the membership grade of industrial water, agricultural water, environmental protection water, and miscellaneous water under water quality, respectively.

In the second line of the fuzzy expected value matrix, 0.304, 0.306, 0.231, and 0.159 is the membership grade of industrial water, agricultural water, environmental protection water, and miscellaneous water under stable supply, respectively. According to the third line of the matrix, 0.291, 0.297, 0.233, and 0.178 is the membership grade of industrial water, agricultural water, environmental protection water, and miscellaneous water under reasonable price,

respectively. The fourth line of the matrix, 0.326, 0.279, 0.224, and 0.181,is the membership grade of industrial water, agricultural water, environmental protection water, and miscellaneous water under reclaimed water technology, respectively.

$$\overline{S2} = \begin{bmatrix} (0.495,0.554) & (0.473,0.190) & (0.514,0.151) & (0.561,0.106) \\ (0.247,0.554) & (0.272,0.190) & (0.239,0.151) & (0.212,0.106) \\ (0.165,0.554) & (0.148,0.190) & (0.144,0.151) & (0.130,0.106) \\ (0.095,0.554) & (0.109,0.190) & (0.105,0.151) & (0.099,0.106) \end{bmatrix}$$

Among $\overline{S2}$, 0.554, 0.190, 0.151, and 0.106 is the expected membership grade of the water control scheme "1-day supply and 1-day suspension (reclaimed water is supplied for the day of water suspension)," "2-day supply and 2-day suspension (reclaimed water is supplied for the day of water suspension)," "1-day supply and 2-day suspension (reclaimed water is supplied for the day of water suspension)," and "1-day supply and 3-day suspension (reclaimed water is supplied for the day of water suspension)," respectively.

In the first line of the fuzzy expected value matrix, 0.495, 0.247, 0.165, and 0.095 is the membership grade of NTD 15-20/ton, NTD 20-25/ton, NTD 25-30/ton, and NTD 30-35/ton, respectively, under "one-day supply and one-day suspension." According to the second line of the matrix, 0.473, 0.272, 0.148, and 0.109 is the membership grade of NTD 15-20/ton, NTD 20-25/ton, NTD 25-30/ton, and NTD 30-35/ton, respectively, under "two-day supply and two-day suspension." In the third line of the matrix, 0.514, 0.239, 0.144, and 0.105 is the membership grade of NTD 15-20/ton, NTD 20-25/ton, NTD 25-30/ton, and NTD 30-35/ton, respectively, under "one-day supply and two-day suspension." In the fourth line of the matrix, 0.561, 0.212, 0.130, and 0.099 is the membership grade of NTD 15-20/ton, NTD 20-25/ton, NTD 25-30/ton, and NTD 30-35/ton, respectively, under "one-day supply and three-day suspension."

(2) The fuzzy mode

As for the fuzzy mode of assessment items

$$\max\left\{\frac{102.02}{\text{water quality}}, \frac{50.25}{\text{stable supply}}, \frac{44.75}{\text{reasonable price}}, \frac{48.25}{\text{reclaimed water technology}}\right\} = \frac{102.02}{\text{water quality}}$$

Hence, analysis of the survey results indicates that water quality is the most important assessment item.

The fuzzy mode of choosing the water reuse target is

$$\max\left\{\frac{66.2125}{\text{industrial water}}, \frac{76.8375}{\text{agricultural water}}, \frac{62.6125}{\text{environmental protection water}}, \frac{40.9875}{\text{miscellaneous water}}\right\}$$

$$= \frac{76.8375}{\text{agricultural water}}$$

Therefore, most people think that agriculture water is the best reuse target.

As for the fuzzy mode of the water control scheme

$$\max\left\{\frac{135.8507}{\text{1-day and 1-day}}, \frac{46.5511}{\text{2-day and 2-day}}, \frac{37.0552}{\text{1-day and 2-day}}, \frac{26.0536}{\text{1-day and 3-day}}\right\}$$

$$= \frac{135.8537}{\text{1-day and 1-day}}$$

Analysis of the survey results indicates that, when the government controls water use by supplying water district after district, among the four water control schemes, the public finds

the "1-day supply and 1-day suspension (reclaimed water is supplied for the day of water suspension)" plan to be most acceptable.

The fuzzy mode of acceptance of the reclaimed water price is

$$\max\left\{\frac{118.0512}{\text{NTD15}-20/\text{ton}}, \frac{62.3537}{\text{NTD20}-25/\text{ton}}, \frac{40.4502}{\text{NTD25}-30/\text{ton}}, \frac{25.1588}{\text{NTD30}-35/\text{ton}}\right\} = \frac{118.0512}{\text{NTD15}-20/\text{ton}}$$

Therefore, the public finds the pricing of NTD15-20/ton of reclaimed water to be acceptable.

(3) Correlation coefficient of membership grade

Table 2. Correlation Coefficient of Membership Grade on Reclaimed Water Target Selection

Assessment Item / Water Reuse Target	Water Quality	Stable Supply	Reasonable Price	Reclaimed Water Technology
Industrial Water	-0.1351	0.1861	0.0700	0.0345
Agricultural Water	0.2740	0.1718	-0.2223	-0.0226
Environmental Protection Water	0.1002	-0.2598	-0.0258	0.1855
Miscellaneous Water	-0.2198	-0.0516	0.1809	-0.2472

Table 2 shows the analysis of the assessment item "water quality," in which agricultural water and environmental protection water have a positive correlation. It is thus inferred that water quality has a positive evaluation tendency for agricultural water and environmental protection water in terms of public acceptance.

As for the analysis of the assessment item "stable supply," industrial water and agricultural water have a positive correlation. It is thus inferred that stable supply has a positive evaluation tendency for industrial water and agricultural water in terms of public acceptance.

As for the analysis of the assessment item "reasonable price," miscellaneous water and industrial water have a positive correlation. It is thus inferred that reasonable price has a positive evaluation tendency for miscellaneous water and industrial water in terms of public acceptance.

As for the analysis of the assessment item "reclaimed water technology," environmental protection water and industrial water have a positive correlation. It is thus inferred that reclaimed water technology has a positive evaluation tendency for environmental protection water and industrial water in terms of public acceptance.

From the water reuse target "Industrial Water" point of view, it is found that the assessment item "Stable Supply" has a relatively high positive correlation with other items (i.e., Reasonable Price, Reclaimed Water Technology, and Water Quality). "Industrial Water" needs the "Stable Supply" from the reclaimed water in terms of public acceptance.

"Agricultural Water" must regard "Water Quality" as more important, "Environmental

Protection Water" needs "Reclaimed Technology," and "Miscellaneous Water" must consider "Reasonable Price" from the reclaimed water in terms of public acceptance.

Table 3. Correlation Coefficient of Membership Grade on Water Control Scheme

Water Control Scheme / Reclaimed Water Price	1-day Supply and 1-day Suspension (reclaimed water is supplied for the day of water suspension)	2-day Supply and 2-day Suspension (reclaimed water is supplied for the two days of water suspension)	1-day Supply and 2-day Suspension (reclaimed water is supplied for the two days of water suspension)	1-day Supply and 3-day Suspension (reclaimed water is supplied for the three days of water suspension)
NTD 15-20/ton	0.4553	-0.2720	-0.5538	-0.4515
NTD 20-25/ton	-0.1510	0.0479	0.3158	0.1525
NTD 25-30/ton	-0.2441	0.2935	0.5684	0.5223
NTD 30-35/ton	-0.6330	0.2949	0.3832	0.4687

Table 3 shows that the water control scheme "1-day supply and 1-day suspension" and the reclaimed water price "NTD 15-20/ton" have a positive correlation. If the government uses reclaimed water on water suspension days to control water usage, under the 1-day supply and 1-day suspension plan, the public finds the pricing of NTD 15-20 per ton of reclaimed water to be acceptable. Under the 1-day supply and 2-day suspension plan, as well as the 1-day supply and 3-day suspension plan, the public accepts the pricing of NTD 20-30 per ton for reclaimed water. Under the 2-day supply and 2-day suspension plan, they accept the pricing of NTD 30-35 per ton for reclaimed water.

In terms of the analysis of reclaimed water price "NTD 15-20/ton," the water control scheme "1-day supply and 1-day suspension" has a relatively high positive correlation with other schemes. The reclaimed water prices "NTD20-25/ton," "NTD 25-30/ton," and "NTD30-35/ton" could be accepted under the water control schemes "2-day supply and 2-day suspension," "1-day supply and 2-day suspension," and "1-day supply and 3-day suspension," respectively.

5. Conclusion

(1) When reclaimed water is used as a source of water, the public ranked four evaluation items in order of importance from most to least important: water safety, stable supply, reasonable pricing, and reclaimed water treatment technology.

(2) Regarding water safety, the public considers it a top priority to consider the safety of water quality when reclaimed water is directed to agricultural use. Regarding stable supply, the public considers it a top priority to consider the stable supply of water when reclaimed water is used for industrial purposes. Regarding reasonable pricing, the public considers it a top priority to consider whether pricing is reasonable when reclaimed water is directed to urban use. Regarding reclaimed water treatment technology, the public finds it a top priority to consider the technology available to treat reclaimed water when it is directed to ecological use.

(3) If the government controls water use by supplying water district after district, among the four water control practices, the public finds the "1-day supply and 1-day suspension" plan most acceptable, followed by "2-day supply and 2-day suspension," then "1-day

supply and 2-day suspension," and finally, "1-day supply and 3-day suspension."

(4) Currently, the average price for tap water is NTD 11.5 per ton. If the government uses reclaimed water on water suspension days to control water usage, under the 1-day supply and 1-day suspension plan, the public finds the pricing of NTD 15-20 per ton of reclaimed water to be acceptable. Under the 1-day supply and 2-day suspension plan, as well as the 1-day supply and 3-day suspension plan, the public accepts the pricing of NTD 20-30 per ton for reclaimed water. Under the 2-day supply and 2-day suspension plan, they accept the pricing of NTD 30-35 per ton for reclaimed water.

(5) Using reclaimed water means that the same drop of water is used at least twice, and this is an important trend for water sustainability throughout the world. Taiwan should regard reclaimed water as a legitimate water source, and keeping the public informed on and incentivized to use reclaimed water should help alleviate the negative impacts that extreme weather conditions have on the water supply.

(6) Taiwan's tap water prices have been lower than that of other countries for a very long time, which has resulted in a general tendency among the public to not cherish their water supply. Therefore, the government should increase the price of tap water by a reasonable amount. This study demonstrated that the public can accept a relatively high price for reclaimed water.

(7) Technology for reclaimed water treatment is quite expensive. If the public accepts highly priced reclaimed water, in the face of a potential water shortage in the future, the government could consider supplying high-priced reclaimed water on water suspension days, instead of the original plan of shutting off water supply completely on water suspension days.

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