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Prioritizing selection criteria of distributed circular water systems: A fuzzy based multi-criteria decision-making approach

Yu-Chen Lee [a,*], Fernanda Leite [a], Katherine Lieberknecht [b]

[a] Department of Civil, Architectural and Environmental Engineering, The University of Texas at Austin, Austin, TX, USA

[b] Community and Regional Planning, School of Architecture, The University of Texas at Austin, Austin, TX, USA

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ABSTRACT

Extreme weather events, population growth, and industrial activities all contribute to the worldwide water crisis. The traditional linear water management model is one of the causes of global water shortage, following a take-make-use-dispose pattern that is both environmentally and economically unsustainable. The circular economy has been proposed to mitigate water shortages, encouraging a paradigm shift in urban water systems. A circular water system seeks to close the water loop by reducing consumption, recovering natural resources, and minimizing waste. Compared with a centralized water system, a distributed water system is more flexible and resilient as it allows neighborhoods to prepare for unexpected stressor events. However, there have been no thorough investigations of essential factors that primarily impact the decision-making process of implementing distributed water systems. Thus, this study aims to uncover significant selection criteria that impact the assessment of feasible options to assist in the planning phase. The researchers proposed a systematic framework to develop criteria and their relative weights for selecting the most appropriate distributed water system to be deployed in a neighborhood. The authors identified four criteria and seventeen sub-criteria through a comprehensive literature review. Then, the Fuzzy Delphi Method (FDM) was performed to collect experts' opinions to remove insignificant sub-criteria. Subsequently, a Fuzzy Analytical Hierarchy Process (FAHP) was conducted to obtain relative weights of the eleven remaining sub-criteria via pairwise comparison. In conclusion, this study contributes to the body of knowledge by proposing selection criteria to facilitate the assessment of implementing distributed water systems. In addition, the proposed framework is applicable to other urban systems, such as food and energy.

1. Introduction

In 2020, 3.6 billion people were living without access to proper sanitation facilities, and 2 billion people lacked a reliable source of drinking water (World Health Organization, 2021). Based on present trends, the worldwide water demand is anticipated to be 40% higher than available supplies by 2030. In other words, only 81 percent of the global population will have access to safe potable water by 2030, leaving 1.6 billion people without such services (World Health Organization, 2021). Global water scarcity is exacerbated by climate change, population growth, as well as agricultural and industrial activities (Delgado et al., 2021). For instance, the increasing global temperature and extreme weather events caused by climate change are influencing the water cycle. Furthermore, the global population is expected to reach 9.8 billion by 2050 (United Nations, 2017), resulting in a growing demand for safe water management services. Industrial activities account for 19 percent of global water consumption (Ritchie and Roser, 2017) and generate wastewater that might be discharged without proper treatment, posing further threats to the worldwide water shortage.

Water resource challenges are crucial for people all around the world since they can lead to a wide range of economic, environmental, and social issues. In the context of expanding urbanization, intensifying water-related challenges strengthen the need for rethinking and redesigning urban water systems. Advocates of circular economy have promoted its use in response to the water crisis to facilitate a shift in the current water management paradigm. Conventionally, water resources management is in a linear model that follows a "take-make-use-dispose" pattern. That is, the traditional linear approach continuously removes water without replenishing it, making accessing safely managed water services even more challenging. The linear water model is unsustainable in both economic and environmental aspects. A circular economy approach, on the other hand, offers the potential for overcoming water-

* Corresponding author.
E-mail addresses: yuchenlee@utexas.edu (Y.-C. Lee), fernanda.leite@utexas.edu (F. Leite), klieberknecht@utexas.edu (K. Lieberknecht).

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related challenges in a more sustainable, equitable, resilient, and efficient manner (Delgado et al., 2021). Incorporating circular economy principles in urban water systems is promising for repeated water use through minimizing waste, recovering resources, and reducing consumption.

Given the benefits a circular model can offer, an increasing amount of research has been carried out on circular water systems (Bouziotas et al., 2019; Delgado et al., 2021; Eshetu Moges et al., 2018; Gleason Espíndola et al., 2018; Makropoulos et al., 2018; Roest et al., 2016; Smol et al., 2020). With the help of cutting-edge technologies, researchers have developed a wide variety of centralized and distributed circular water systems. While centralized water systems can serve greater demands, establishing such services requires a more significant capital investment and more extended time (Bouziotas et al., 2019; Chirisa et al., 2017; Massoud et al., 2009; Rabaey et al., 2020; United Nations, 2015). Large-scale water systems use more energy and are less likely to restore resources (Daigger et al., 2019; Leigh and Lee, 2019). Conversely, deploying distributed water systems costs less in time and money, and is more flexible in providing services on a smaller scale to adapt to the needs of a particular neighborhood or community (Chirisa et al., 2017; Daigger, 2009; United Nations, 2015). Furthermore, distributed systems can properly function even when a centralized system is disrupted, which helps cities prepare for unforeseen stressors or shocks (Leigh and Lee, 2019). Accordingly, this research places emphasis on the adoption of distributed circular water systems at the neighborhood scale.

While numerous research efforts have been dedicated to developing and inventing leading-edge circular water technologies, key factors that influence the decision-making process have not been fully explored. Therefore, this study aims to bridge this gap by identifying critical criteria and sub-criteria that impact the assessment of feasible options and assist stakeholders in selecting the most appropriate one for implementation. Our approach employs the Fuzzy Delphi Method (FDM) and the Fuzzy Analytical Hierarchy Process (FAHP) to gather expert opinions to form a consensus on the level of importance of all identified criteria/sub-criteria. The authors eliminated irrelevant factors via FDM and derived relative weights for each criterion and sub-criterion employing FAHP. The intellectual contributions of this study consist of establishing and assessing selection criteria for distributed circular water system implementations. As a result of the research's practical contributions, the researchers developed a fuzzy multi-criteria decision-support model that municipalities can use to identify community priorities. The city government and community members are in charge of making decisions about adopting neighborhood-scaled water systems, and the findings of this research may help them examine all feasible solutions. Moreover, the general process of determining the relative weights of criteria can also be extended to other systems, such as energy and food systems.

2. Literature review

2.1. Circular economy in water systems

The typical paradigm of urban water management is a centralized water system, which distributes water from numerous sources to metropolitan areas, and has consistently benefited cities (Bouziotas et al., 2019). Nonetheless, the drawbacks of centralized systems, including land scarcity, complexity, and cost-effectiveness, raise the need for more sustainable water systems (Bajpai et al., 2019). Compared to centralized water systems, distributed (or decentralized) water systems provide services to a smaller population, including but not limited to buildings, neighborhoods, or communities. There has been some debate on whether decentralized water systems are more advantageous. For example, distributed water supply allows for greater water conservation and reuse and lowers the cost of replacing water infrastructure (Mbavarira and Grimm, 2021). Moreover, distributed water systems combine all operations, including collection, recycling, and reuse, on a smaller scale and near the source, making such systems more efficient and adaptable (Bajpai et al., 2019). Furthermore, a distributed water system can benefit the area it serves because it improves equity by providing service in communities with uneven infrastructure investments (Leigh and Lee, 2019).

Table 1 summarizes real-world cases of adopting distributed water systems that integrate circular economy concepts worldwide. The comprehensive review includes practices on six continents, which are further categorized into "Wastewater treatment," "Stormwater harvesting," "Rainwater harvesting," and "Air-conditioning condensate harvesting" according to the type of water systems. Among wastewater treatment categories, constructed wetland (CW) is the most common category that has the potential to enhance water quality through replicating natural processes and the interaction of vegetation, soils, and microbial assemblages on the wetland (Vymazal, 2010). Membrane Biological Reactor (MBR) is another commonly used technique that utilizes the membrane as a filtration to eliminate the solid debris generated during the biological process to provide a sanitized effluent product. The common uses of stormwater/rainwater/air-conditioning condensate harvesting systems are collecting and storing water for cooling buildings, toilet flushing, and irrigation.

In compiling the distributed water system implementation practices, the authors also gathered vital factors that might impact the decision-making. Table 2 provides a list of 17 selected factors, which may be further categorized into four categories, including "Technical," "Economic," "Environmental," and "Social." The four criteria and 17 sub-criteria served as the basis for this study and were used in subsequent procedures, which will be explained in Section 3.

2.2. Fuzzy Delphi Method and Fuzzy Analytical Hierarchy Process

The Delphi method (DM) was proposed by Dalkey and Helmer (1963) to acquire trustworthy agreement among an expert panel, which comprises rounds of surveys with controlled feedback to reach a consensus. In a Delphi study, participants are a group of experts identified based on their expertise and experience in a specific field of study, and they are anonymous to each other for the purpose of minimizing dominance bias (Dalkey and Helmer, 1963; Hallowell and Gambatese, 2010). Experts are asked to answer questions around a specific issue, and statistically analyzed responses are provided after completing each round to prevent collective unconscious bias (Dalkey and Helmer, 1963; Hallowell and Gambatese, 2010). Participants have the chance to revisit and reconsider their initial judgments in light of the analyzed results from the previous round. The survey iteration ends when Kendall's coefficient of concordance passes the predefined thresholds.

As Hallowell and Gambatese (2010) suggest, a minimum of three rounds are essential to achieve group consensus. The traditional DM is costly and time-consuming given the necessity of conducting multiple rounds of questionnaires, which may result in subjective outcomes due to the decrease in response rate (Hwang and Lin, 1987; Ishikawa et al., 1993; Karam et al., 2021; Liu, 2013; Yusof et al., 2022). The primary flaw of the conventional DM is the lengthy and repetitive cycle that may contribute to data leakage and loss (Bojadziev and Bojadziev, 2007). In order to resolve such constraints, researchers developed the FDM that integrates fuzzy numbers with the conventional DM, which is beneficial in reducing the fuzziness of experts' mutual understanding and increasing effectiveness and quality (Ishikawa et al., 1993). In the past few decades, the FDM has been utilized for different purposes across industries (Chang et al., 2011; Dapari et al., 2017; Garai and Kumar, 2013; Habibi et al., 2015; Kuo and Chen, 2008; Lee et al., 2021; Mohamed Yusoff et al., 2021; Yusof et al., 2022), including screening and forecasting. The FDM has often been integrated with other techniques for broader applications, such as the FAHP.

The Analytical Hierarchy Process (AHP) was presented by Saaty (1984) to solve a complex problem by dividing the problem into a

Table 1
Implementation of distributed circular water systems around the globe.

Continent	Country	Category	Features	References
Africa	Egypt	• Wastewater treatment	• Constructed Wetland (CW) • Up-flow anaerobic sludge blanket	Abdel-Shafy et al. (2009)
	Kenya	• Wastewater treatment	• CW	Mburu et al. (2013)
	Kenya	• Wastewater treatment	• CW	Bojcevska and Tonderski (2007)
Asia	Bahrain	• Air-conditioning condensate harvesting	• Collection and storage • Toilet flushing • Landscaping • Washing	Guz (2005)
	China	• Wastewater treatment	• CW	Ji et al. (2007)
	China	• Wastewater treatment	• CW	Li et al. (2009)
	China	• Wastewater treatment	• CW	Li et al. (2008)
	China	• Wastewater treatment	• Membrane bioreactor (MBR)	Yang et al. (2021)
	India	• Air-conditioning condensate harvesting	• Collection and storage • Cooling buildings • Irrigation	Malloy (2021)
	Israel	• Air-conditioning condensate harvesting	• Collection and storage • Cooling buildings • Irrigation	Malloy (2021)
	Jordan	• Wastewater treatment	• CW	Nivala et al. (2019)
	Malaysia	• Wastewater treatment	• CW	Sim et al. (2008)
	Malaysia	• Rainwater harvesting	• Collection and storage • Cooling buildings	Venkiteswaran et al. (2017)
	Sri Lanka	• Wastewater treatment	• CW	Jinadasa et al. (2006)
	Thailand	• Wastewater treatment	• CW	Klomjek and Nitisoravut (2005)
	United Arab Emirates	• Air-conditioning condensate harvesting	• Collection and storage • Cooling buildings	Frechette et al. (2006)
Australia	Australia	• Rainwater harvesting	• Collection and storage • Filtration • Potable water supply	Cooperative Research Centre for Water Sensitive Cities (n.d.)
	Australia	• Wastewater treatment • Stormwater harvesting Rainwater harvesting	• MBR • Collection and storage • Irrigation • Cooling buildings	Cooperative Research Centre for Water Sensitive Cities (n.d.)
	Australia	• Rainwater harvesting	• Collection and storage • Cooling buildings	Smart Water Fund (2010)
Europe	Berlin	• Rainwater harvesting	• Collection and storage • Filtration	Kuras (n.d.)
	Germany	• Wastewater treatment	• MBR	Meuler et al. (2008)
	Italy	• Wastewater treatment	• CW	Liquete et al. (2016)
	Netherlands	• Rainwater harvesting	• Collection and storage	Bouziotas et al. (2019)
	United Kingdom	• Air-conditioning condensate harvesting	• Collection and storage • Cooling buildings • Irrigation	Malloy (2021)
North America	EI Salvador	• Wastewater treatment	• CW	Katsenovich et al. (2009)
	United States	• Wastewater treatment	• MBR	National Blue Ribbon Commission for Onsite Non-potable Water Systems (2018)
	United States	• Wastewater treatment • Rainwater harvesting	• CW • Collection and storage • Filtration • Irrigation	National Blue Ribbon Commission for Onsite Non-potable Water Systems (2018)
	United States	• Wastewater treatment • Rainwater harvesting	• MBR • Collection and storage • Irrigation • Cooling buildings	Seattle Public Utilities and Seattle Public Utilities (2008)
	United States	• Rainwater harvesting	• Collection and storage • Filtration • Irrigation	National Blue Ribbon Commission for Onsite Non-potable Water Systems (2018)
	United States	• Stormwater harvesting	• Collection and storage • Irrigation	Meridian Institute et al. (2022)
	United States	• Air-conditioning condensate harvesting	• Collection and storage • Irrigation	Guz (2005)
	United States	• Air-conditioning condensate harvesting	• Collection and storage • Cooling buildings	U.S. Environmental Protection Agency (2014)
	United States	• Stormwater harvesting	• Collection and storage • Irrigation	Water in Motion (n.d.)
South America	Brazil	• Wastewater treatment	• CW	Sarmento et al. (2013)
	Brazil	• Stormwater harvesting	• Collection and storage • Irrigation • Car washing	Shubo et al. (2022)

Table 2
Selection criteria/sub-criteria identified.

Criteria	Sub-Criteria	References
C1. Technical	S1. Ease of deployment	Arora et al. (2015); Capodaglio (2017); Makropoulos et al. (2018); McLean and Roggema (2019); Wang et al. (2020)
	S2. Ease of operation and maintenance by end-users	Capodaglio (2017); Cipolletta et al. (2021); McLean and Roggema (2019); Roest et al. (2016)
	S3. Reliability	Arora et al. (2015); Bouziotas et al. (2019)
C2. Economic	S4. Initial investment	Bouziotas et al. (2019); Capodaglio (2017); Gleason Espíndola et al. (2018); Makropoulos et al. (2018); McLean and Roggema (2019); Rodríguez et al. (2020); Roefs et al. (2017); Roest et al. (2016); Wang et al. (2020)
	S5. Operation and maintenance costs	Arora et al. (2015); Bouziotas et al. (2019); Capodaglio (2017); Gleason Espíndola et al. (2018); Makropoulos et al. (2018); Rodríguez et al. (2020); Roefs et al. (2017); Roest et al. (2016)
	S6. Efficiency	Bouziotas et al. (2019; Capodaglio (2017); Gleason Espíndola et al. (2018)
	S7. Available financial resources	Cipolletta et al. (2021)
C3. Environmental	S8. Noise pollution	McLean and Roggema (2019); Rodríguez et al. (2020)
	S9. Unpleasant odor	Capodaglio (2017); Eshetu Moges et al. (2018); Makropoulos et al. (2018); McLean and Roggema (2019); Roest et al. (2016)
	S10. Reduction in water consumption	Bouziotas et al. (2019); Gleason Espíndola et al. (2018); McLean and Roggema (2019); Rodríguez et al. (2020); Roest et al. (2016); Santos et al. (2021); Smol et al. (2020); Wang et al. (2020)
	S11. Reduction in wastewater	Bouziotas et al. (2019); Eshetu Moges et al. (2018); Gleason Espíndola et al. (2018); McLean and Roggema (2019); Roest et al. (2016); Santos et al. (2021); Smol et al. (2020); Wang et al. (2020)
	S12. Energy requirements	Arora et al. (2015); Bouziotas et al. (2019); Capodaglio (2017); Roefs et al. (2017); Roest et al. (2016); Smol et al. (2020); Wang et al. (2020)
	S13. Reduction in floods	Bouziotas et al. (2019); Gleason Espíndola et al. (2018)
C4. Social	S14. Increasing access to safe water	Bouziotas et al. (2019); Capodaglio (2017); Cipolletta et al. (2021); Gleason Espíndola et al. (2018); McLean and Roggema (2019); Roest et al. (2016); Santos et al. (2021); Wang et al. (2020)
	S15. Public acceptance	Arora et al. (2015); Capodaglio (2017); Cipolletta et al. (2021); McLean and Roggema (2019); Roest et al. (2016)
	S16. Impacts on public health	Arora et al. (2015); Capodaglio (2017); Eshetu Moges et al. (2018); Santos et al. (2021); Smol et al. (2020)
	S17. Regulatory frameworks	Arora et al. (2015); Capodaglio (2017); Cipolletta et al. (2021); Makropoulos et al. (2018); McLean and Roggema (2019); Roest et al. (2016)

hierarchy and using pairwise comparisons to facilitate multi-objective decision-making. The primary input for the AHP is experts' opinions, and the consistency of the expert's judgment is continuously examined throughout the process. However, conventional AHP may subject to bias and subjective judgements as it involves linguistic scale when making pairwise comparison (Hsu et al., 2010). Laarhoven and Pedrycz (1983) developed the FAHP to accommodate the inherent uncertainty and subjectivity of traditional AHP by integrating it with the fuzzy theory (Hsu et al., 2010). The integration of paired comparison matrix and fuzzy numbers has the potential to reflect ambiguity and fuzziness mathematically. Thus, the combination of FDM and FAHP has been widely used in determining the priority of selection criteria (Cheng and Chen, 2012; Cheng and Tang, n.d.; Cheng et al., 2006; Esmailzadeh et al., 2018; Lee and Seo, 2016) to irrelevant indications and evaluate the level of significance of the remaining ones.

In this research study, the authors selected FDM since it is more efficient than the traditional DM, as it only needs one round of survey to screen criteria (Habibi et al., 2015). Also, the proposed method applied FAHP to obtain the relative weight of each criterion. The proposed method will be explained in detail in Section 3.

3. Methodology

Fig. 1 demonstrates the workflow of this research study. The authors started by performing a literature search through Google Scholar to explore common practices of distributed water systems around the globe. Search keywords include "circular economy", "water system", "distributed", "small-scale", "neighborhood-scale", "on-site". Accordingly, Google Scholar generated 832 results. The researchers examined each article carefully and eliminated those that did not fulfill the inclusion criteria based on the title and abstract. In this research, peer-reviewed publications and reports were accepted, and both foreign and domestic instances were reviewed.

Meanwhile, crucial factors that may impact stakeholders during the implementation planning phase were also gathered, which can be used to evaluate all available alternatives for water systems to be deployed within a neighborhood. In total, four potential criteria and 17 sub-criteria were observed. Next, the Fuzzy Delphi Method (FDM) was applied to collect experts' points of view on the level of importance of each factor through an online survey, eliminating six insignificant sub-criteria based on survey results, as described in Section 3.3. Then, the Fuzzy Analytical Hierarchy Process (FAHP) was deployed to determine the relative weight of the four criteria and 11 sub-criteria, which can be utilized in selecting the optimal circular water system for a neighborhood (according to the experts' opinions). The detailed explanation is presented in Section 3.4 and illustrates how FAHP was used to determine the relative weights for the criteria and sub-criteria. Finally, the outcomes of criteria, sub-criteria, and their relative weight and rankings are presented in Section 4.

3.1. Expert qualifications

The definition of an expert is 'someone with special skills or knowledge evidenced by leadership in professional organizations, holding office in a professional organization, presenter at national conventions, published in recognized journals,' as suggested by Cabaniss (2001). To achieve high uniformity across experts, the recommended minimum sample size for Fuzzy Delphi research is ten experts (Adler and Ziglio, 1996; Jones and Twiss, 1978; Mohamed Yusoff et al., 2021). The authors determined the qualification criteria for an effective investigation. The defined qualifications include: (1) possessing at least a bachelor's degree in related fields and (2) at least five years of

Fig. 1. Research method.

Table 3
TFNs for Five-point Likert scale.

Linguistic expression	Corresponding TFNs
Very Unimportant	(0, 0, 0.25)
Unimportant	(0, 0.25, 0.5)
Moderately Important	(0.25, 0.5, 0.75)
Important	(0.5, 0.75, 1)
Very Important	(0.75, 1, 1)

experience in the circular economy, water systems, or related fields. The experts involved in this study were carefully examined to ensure eligibility. Also, this research utilized the snowball sampling method, which is a recruiting strategy in which participants in a survey are encouraged to assist researchers in identifying additional possible respondents (Noy, 2008; Patton, 2002). Overall, 12 experts participated in the FDM survey, and eight experts were involved in the FAHP questionnaire.

3.2. Data collection

In this study, survey questions for FDM and FAHP were developed and tested in Qualtrics®, which is a web-based software that enables users to generate surveys and collect responses. Both surveys have obtained approval from the Institutional Review Board (IRB) at the University of Texas at Austin to ensure researchers follow all the requirements that protect the human rights of participants. The definition of each identified factor was provided for participants. Furthermore, the sequence of survey questions were randomly assigned to eliminate question order bias. Additionally, demographic information was recorded in both surveys for later analyses. The two questionnaires were distributed via direct email to experts or LinkedIn messaging. Survey responses for FDM were collected from February to March 2022. In total, 75 invitations were sent, and 12 completed responses were received. Survey responses for FAHP were gathered between March and April 2022. The questionnaire was distributed 59 times, and eight complete responses were submitted.

3.3. Fuzzy Delphi Method

As presented by Habibi et al. (2015), the procedure of FDM used in this research is described as follows:

(1) Selecting a suitable fuzzy set for fuzzification of linguistic expressions.

Choosing an appropriate fuzzy spectrum for the fuzzification of participants' linguistic phrases is the first step in FDM for screening items. While there are various ways to develop fuzzy spectra, common spectra can be used in this process. A set of triangular fuzzy numbers (TFNs) was determined through a five-point Likert scale on the importance of factors in this study, as shown in Table 3. The five-point Likert scale on the significance is then used in developing survey questions. The linguistic levels are "very unimportant," "unimportant," "moderately important," "important," and "very important," and experts were asked to specify the level of importance for each criterion as illustrated in Fig. 2.

(2) Fuzzy aggregation

The results were gathered and transformed into TFNs. There are various debates on fuzzy aggregation, such as the geometric mean method. The average method was selected for fuzzy aggregation among all the proposed methods to avoid the impact of optimists or pessimists on the result. That is, if an expert's response is expressed as (l, m, u), the fuzzy aggregation is the average of all experts' opinions.

$$F_{average} = \left(\frac{\sum l}{n}, \frac{\sum m}{n}, \frac{\sum u}{n}\right) = (l_j, m_j, u_j), j = 1, 2, \ldots, k$$

where n = number of experts.

k = number of criteria

(3) Defuzzification

The values should be defuzzified once expert opinions have been fuzzy aggregated. Defuzzification involves transforming the aggregated fuzzy set to a crisp and understandable value a_j. For the sake of simplicity, the following describes the center of gravity method used in the study, which is one of the most straightforward defuzzification techniques based on the average fuzzy values:

$$a_j = \frac{l_j + m_j + u_j}{3}, j = 1, 2, \ldots, k$$

(4) Determining the threshold for screening criteria

The final step in FDM is selecting a proper threshold for screening, which is 0.7, as suggested by Habibi et al. (2015). If the crisp value obtained from the previous step is larger than or equal to 0.7, the factor is evaluated as qualified. On the contrary, if the crisp value is less than

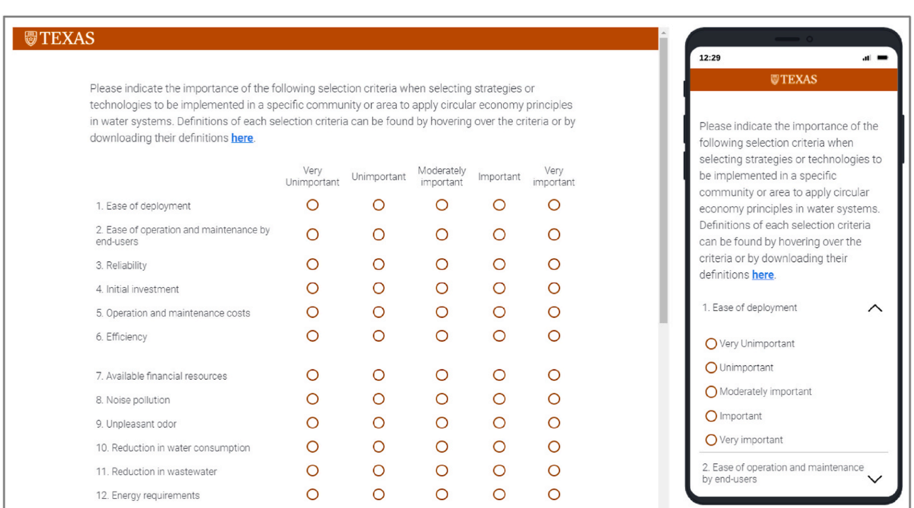

Fig. 2. Example of FDM survey questions.

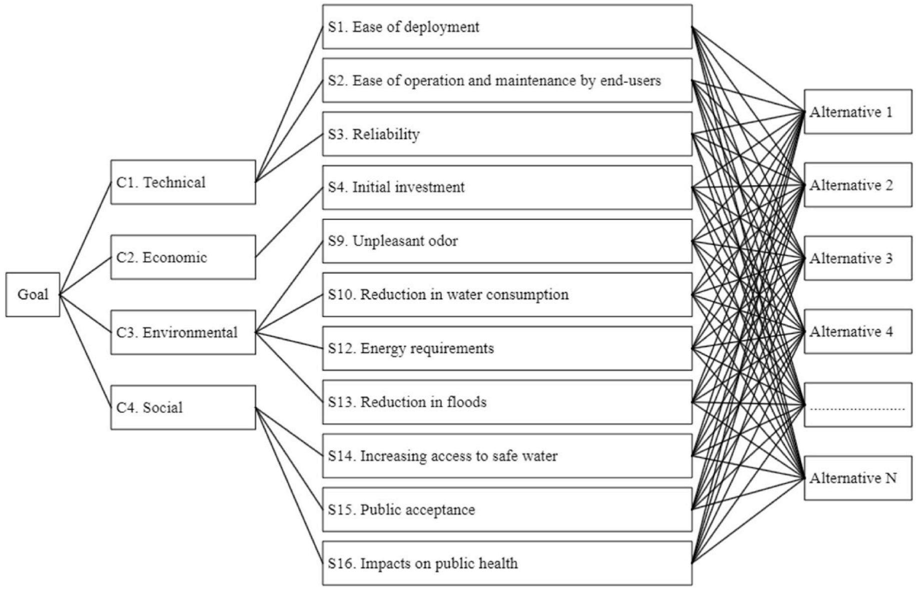

Fig. 3. The hierarchy structure of FAHP of the study.

0.7, the item is eliminated.

3.4. *Fuzzy Analytical Hierarchy Process*

This study adopted the FAHP proposed by Laarhoven and Pedrycz (1983). The following illustrates the procedure of FAHP in this study:

(1) Define problem and hierarchy structure

To ensure effective evaluation, the first step in deploying FAHP is to pinpoint the complex issue that needs to be addressed. The decision problem in this study is to prioritize the selection criteria for implementing distributed circular water systems at a community level, which is also the first layer of the FAHP hierarchy. The assessment criteria and criteria layers can be developed through collaborative discussion and reviewing the literature. In the proposed methodology, the results of the FDM study were used to establish the FAHP hierarchy structure, as shown in Fig. 3.

(2) Determine fuzzy pairwise comparison matrices

The fuzzy matrices employed in this work are described in Fig. 4 and Table 4, where the authors leveraged a five-point Likert scale for gathering experts' opinions. In the FAHP questionnaire, participants were asked to rate the relative importance of two provided criteria or sub-criteria, as depicted in Fig. 5. The participant should choose the "Strongly more important" choice to the left of the "Equally important" option if the left criterion is significantly more important than the right one, and vice versa. After that, the survey findings are converted into TFN sets for later calculations.

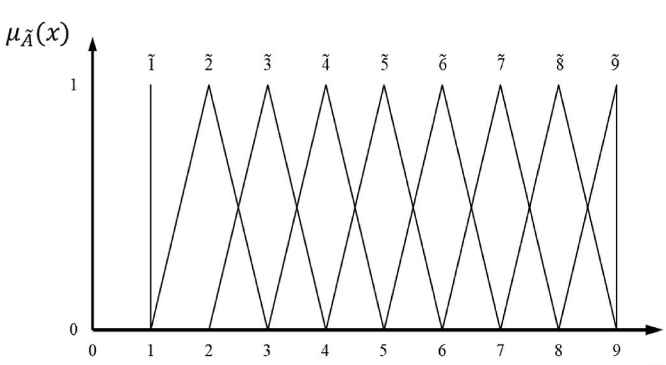

Fig. 4. Fuzzy number scale.

Table 4
The fuzzy paired comparison matrices of this study.

Linguistic expression	Corresponding matrices
Absolutely more important	(9, 9, 9)
Very strongly more important	(6, 7, 8)
Strongly more important	(4, 5, 6)
Weakly more important	(2, 3, 4)
Equally important	(1, 1, 1)

(3) Defuzzification

Defuzzification entails transforming fuzzy numbers into definite values that are easy to understand. The Centroid method was adopted in this step to complete defuzzification for simplicity.

$$W_i = \frac{W_{\alpha i} + W_{\beta i} + W_{\delta i}}{3}$$

Where W_i = defuzzified value

$W_{\alpha i}$ = The value at the right end of the fuzzy weight
$W_{\beta i}$ = The fuzzy weight's value with a membership degree of 1
$W_{\delta i}$ = The value at the left end of the fuzzy weight

(4) Check the consistency ratio

For each pairwise comparison matrix, it is essential to ensure judgements are consistent. As introduced by Saaty (1984) and implemented in contemporary studies (Kaganski et al., 2018; Kustiyahningsih et al., 2020; Lee and Seo, 2016; Lyu et al., 2020; Vinogradova-Zinkevič et al., 2021), Consistency Ratio (CR) is typically used as a measure to evaluate consistency, which is calculated by Consistency Index (CI) and Random Index (RI). CI is calculated as follows:

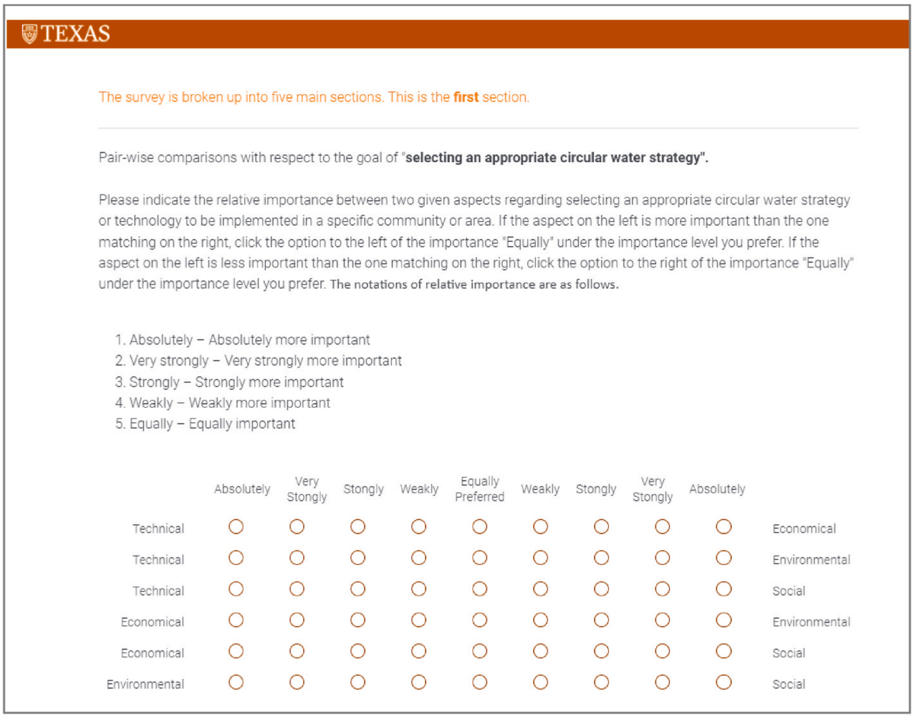

Fig. 5. Example of FAHP survey questions.

$$\text{CI} = \frac{\lambda_{max} - n}{n - 1}$$

Where λ_{max} = The largest eigenvalue derived from the matrix

n = The number of criteria

RIs are values that have been pre-calculated by Saaty (1984) and can be found in published tables. Then, CR is obtained by the following formula:

$$\text{CR} = \frac{CI}{RI}$$

If CR is less than or equal to 0.1 (10%), the inconsistency level is considered acceptable for the pairwise comparison. On the other hand, the judgements are considered too inconsistent if CR is larger than 0.1, thus should be revisited and revised.

(5) Normalization of relative weights

Finally, the defuzzified values were normalized as follows, and the relative weights for each criterion were obtained.

$$NW_i = \frac{W_i}{\sum_{i=1}^{n} W_i}$$

The ranking and selection criteria can be used to evaluate all the alternatives and determine the most appropriate circular water system to be adopted.

4. Results and findings

As shown in Table 2, four criteria and 17 sub-criteria were identified through literature review on related studies in circular water systems. Afterwards, one round of FDM and one round of FAHP were conducted subsequently to evaluate the identified criteria/sub-criteria. The following discusses results of each step.

4.1. Fuzzy Delphi Method survey results

In this study, the FDM is used to filter 17 previously recognized factors. 75 invitations were sent out via direct email or LinkedIn

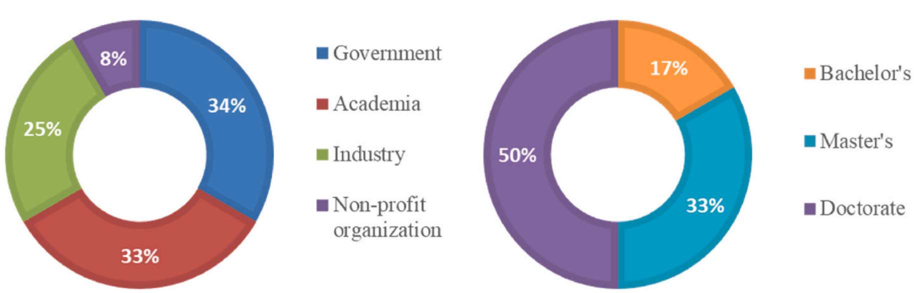

Fig. 6. Participants in the FDM questionnaire by industry/highest level of education.

Table 5
The result of the FDM survey.

Criteria	Sub-Criteria	De-fuzzy	Average	Results
C1. Technical	S1. Ease of deployment	8.667	0.722	Accepted
	S2. Ease of operation and maintenance by end-users	9.750	0.813	Accepted
	S3. Reliability	9.583	0.799	Accepted
C2. Economic	S4. Initial investment	8.667	0.722	Accepted
	S5. Operation and maintenance costs	7.833	0.653	Rejected
	S6. Efficiency	8.250	0.688	Rejected
	S7. Available financial resources	7.583	0.632	Rejected
C3. Environmental	S8. Noise pollution	6.667	0.556	Rejected
	S9. Unpleasant odor	8.917	0.743	Accepted
	S10. Reduction in water consumption	9.083	0.757	Accepted
	S11. Reduction in wastewater	8.083	0.674	Rejected
	S12. Energy requirements	9.083	0.757	Accepted
	S13. Reduction in floods	8.917	0.743	Accepted
C4. Social	S14. Increasing access to safe water	9.083	0.757	Accepted
	S15. Public acceptance	9.333	0.778	Accepted
	S16. Impacts on public health	9.667	0.806	Accepted
	S17. Regulatory frameworks	7.500	0.625	Rejected

message. With a 16% response rate, 12 experts participated in the survey to provide their judgment on each factor. Fig. 6 illustrates the demographic information collected in the questionnaire. Respondents are presently employed by the government, academia, industry, or non-profit organizations. The majority of participants are employed by the government and academic institutions, which account for 34% and 33%, respectively. All respondents possess at least a bachelor's degree, and 83% have a master's degree.

Table 5 presents the analyzed results from FDM survey responses. Six sub-criteria were eliminated during the FDM process, leaving 11 sub-criteria for the FAHP. That is, "S5. Operation and maintenance costs", "S6. Efficiency", "S7. Available financial resources", "S8. Noise pollution", "S11. Reduction in wastewater", and "S17. Regulatory frameworks" factors did not pass the predetermined threshold (0.7) and were deleted from the list.

4.2. Fuzzy Analytical Hierarchy Process survey results

This research used FAHP in order to establish the relative importance of all criteria in the assessment of circular water system options. In total, 59 experts were invited to the survey via email or LinkedIn message. The survey had a 14% response rate, where eight experts were involved in this process. Fig. 7 provides the configuration of survey respondents. 55% of the respondents are from academia, whereas only 9% of them work in a non-profit organization. All the qualified participants completed their bachelor's degrees, and 63% possess a doctorate.

The empirical outcomes of the FAHP application, including weights and rankings of criteria/sub-criteria, are shown in Fig. 8 and Table 6. With a weight of 0.289, the "C1. Technical" aspect is the most significant of the four criteria. The second key aspect is "C3. Environmental," which accounts for 0.221. In terms of sub-criteria, "S16. Impacts on public health", "S14. Increasing access to safe water", and "S13. Reduction in floods" are the top three to be examined, with weights of 0.152, 0.149, and 0.125 respectively. On the other hand, "S1. Ease of deployment", "S15. Public acceptance", and "S12. Ease of operation and maintenance by end-users" are of minor importance during the selection process.

"S3. Reliability" is the most essential factor to examine in the "C1. Technical" category, followed by "S2. Ease of operation and maintenance by end-users." In other words, while planning the implementation of on-site circular water systems, it is crucial to evaluate the systems' capability to provide water that satisfies water quality standards under proper operation. Furthermore, the system should function without the need for repair for an initial period of time. Moreover, operating and maintenance work performed by end-users should be intuitive and straightforward. Under "C2. Economic" criteria, only "S4. Initial investment" passed the threshold, with a 0.072 relative weight. This can be interpreted as a major concern expressed by the majority of experts involved in this study, while operations and maintenance expenses are less of a concern. "C3. Environmental" is the second most significant aspect that experts identified, meaning that the potential effects of distributed circular water systems, whether positive or negative, should be carefully examined. In this category, "S13. Reduction in floods" and "S10. Reduction in water consumption" are top two sub-criteria, illustrating experts' expectation on the ideal system for solving flood issues while reducing water consumption simultaneously, resulting in a more resilient neighborhood/community. Last but not least, "S16. Impacts on public health" and "S14. Increasing access to safe water" are two of the most important sub-criteria that fall under "C4. Social", indicating that

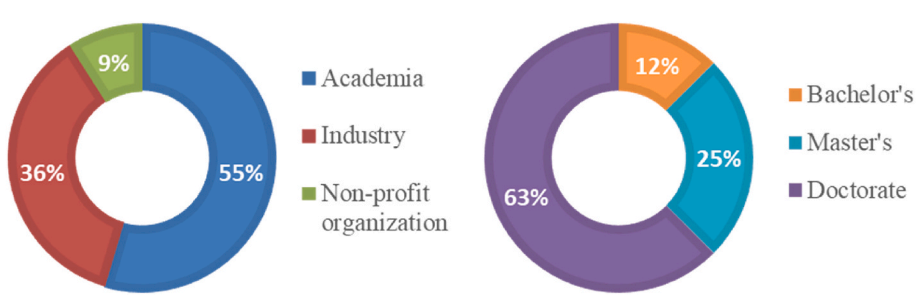

Fig. 7. Participants in the FAHP survey by industry/highest level of education.

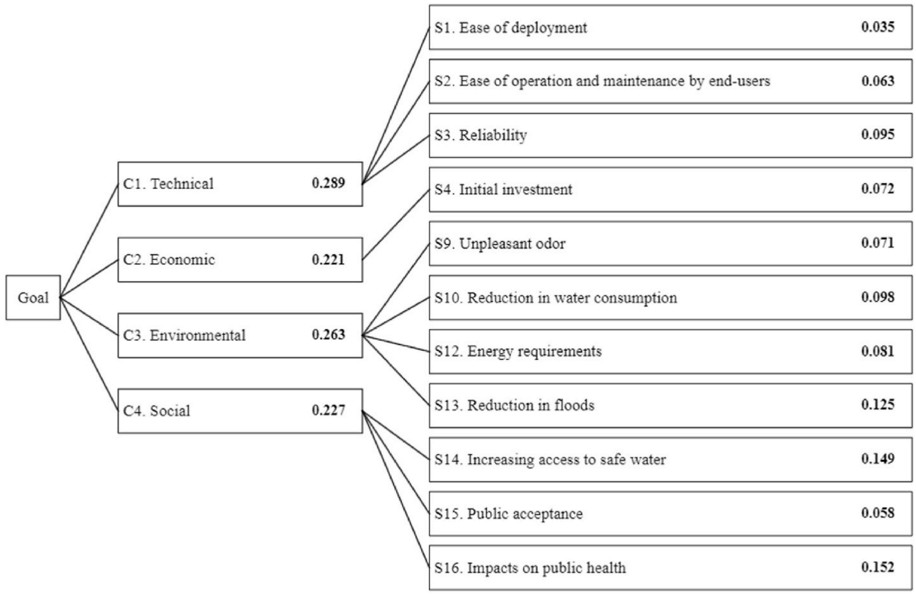

Fig. 8. The weights of circular water system selection model.

Table 6
FDM and FAHP results comparison.

Fuzzy Delphi Method Results					Fuzzy Analytical Hierarchy Process Results			
Criteria	Sub-Criteria	Defuzzified Value	Average Value	Results	Criteria Weight	Criteria Rank	Sub-criteria Weight	Sub-criteria Rank
C5. Technical	S1. Ease of deployment	8.667	0.722	Accepted	0.289	1	0.035	11
	S2. Ease of operation and maintenance by end-users	9.750	0.813	Accepted			0.063	9
	S3. Reliability	9.583	0.799	Accepted			0.095	5
C6. Economic	S4. Initial investment	8.667	0.722	Accepted	0.221	4	0.072	7
	S5. Operation and maintenance costs	7.833	0.653	Rejected			–	–
	S6. Efficiency	8.250	0.688	Rejected			–	–
	S7. Available financial resources	7.583	0.632	Rejected			–	–
C7. Environmental	S8. Noise pollution	6.667	0.556	Rejected	0.263	2	–	–
	S9. Unpleasant odor	8.917	0.743	Accepted			0.071	8
	S10. Reduction in water consumption	9.083	0.757	Accepted			0.098	4
	S11. Reduction in wastewater	8.083	0.674	Rejected			–	–
	S12. Energy requirements	9.083	0.757	Accepted			0.081	6
	S13. Reduction in floods	8.917	0.743	Accepted			0.125	3
C8. Social	S14. Increasing access to safe water	9.083	0.757	Accepted	0.289	3	0.149	2
	S15. Public acceptance	9.333	0.778	Accepted			0.058	10
	S16. Impacts on public health	9.667	0.806	Accepted			0.152	1
	S17. Regulatory frameworks	7.500	0.625	Rejected			–	–

experts are concerned about whether the system has negative effects on public health and whether the system can increase the accessibility of safe potable water.

5. Conclusions

Increasing extreme weather conditions, population expansion, and industrial activities exacerbate the global water shortage. The circular economy has been proposed in response to mitigating water scarcity by facilitating a paradigm change in water management. Incorporating circular economy principles into urban water systems is beneficial for closing the loop of water usage by reducing waste, recovering resources, and lowering consumption. Distributed water systems provide higher resiliency and are more flexible in terms of delivering services on a smaller scale. Even if a centralized system fails, distributed systems retain their functionality, allowing communities to prepare for unanticipated events. Hence, this paper seeks to uncover essential criteria and sub-criteria that affect the evaluation of viable alternatives, intending to support all parties involved in deciding the most suitable solution.

Through literature review, the authors evaluated common distributed water system deployment practices and their determinants worldwide. In the process, four criteria and seventeen sub-criteria were observed. The FDM was then used for screening purposes based on the opinion of an expert panel. The FAHP was used for weighting and ranking all the criteria. As a result, this research contributes intellectually and practically to the body of knowledge. The assessment criteria for implementing neighborhood-scale circular water systems were established using a systematic framework. Practical contributions from the study include a fuzzy multi-criteria decision model that might be implemented in communities and adapted to other urban systems.

Establishing selection criteria for circular water systems at the neighborhood level possesses significant managerial implications. The developed criteria provide practical guidance for municipal authorities and water management companies in the decision-making process. By leveraging these criteria, stakeholders can evaluate and compare various circular water system alternatives based on factors such as water demand, resource availability, environmental impact, and feasibility. This enables informed decisions that align with sustainability objectives and the specific needs of each neighborhood. The application of these selection criteria facilitates efficient resource allocation and supports the implementation of sustainable water management practices. Moreover, the systematic approach provided by the established criteria enhances transparency and accountability in the decision-making process. Ultimately, these managerial implications contribute to the effective deployment of circular water systems, promoting sustainable and resilient water management at the neighborhood level.

A limitation of this research is that the response rates for both FDM and FAHP are relatively low (16% and 14% respectively). The primary reason for this may be the fact that this study was targeted at experts within the field, so the pool of potential respondents was inherently limited. Moreover, the high demand on these professionals' time could have contributed to lower response rates due to their limited availability. Another potential cause is the impact of the COVID-19 pandemic. Since the beginning of the pandemic, it has been observed that the response rates to several surveys have decreased significantly. As noted by Krieger et al. (2023), the household response rate to the US Census American Community Survey dropped from 86.0% in 2019 to 71.2% in 2020. Further impacting our response rate are factors such as our survey topic, the time investment required for thoughtful responses, and the optional nature of participation. Hence, the survey distribution can be further expanded to a wider group of professionals and stakeholders in the future, improving the breadth of perspectives gathered. Another limitation of this study is that the outcomes (criteria/sub-criteria and their relative weight) have not been applied to real-world cases. Therefore, future research efforts can be developed based on the results of this study to help examine all possible circular water systems to be adopted in a specific neighborhood in real-world.

Although the FDM and FAHP methods utilized in this study were effective, there is space for more quantitative approaches in future studies. ANOVA, Principal Components, Factor Analysis, and Fuzzy Entropy could provide new insights and challenge or validate our study's findings. A comparative analysis putting FDM and FAHP against these methods could potentially lead to new insights. Incorporating these techniques into future research would diversify and strengthen methodologies, thereby augmenting decision-making processes in this field.

CRediT authorship contribution statement

Yu-Chen Lee: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Fernanda Leite:** Conceptualization, Supervision, Project administration, Funding acquisition, Writing – original draft, Writing – review & editing. **Katherine Lieberknecht:** Conceptualization, Supervision, Project administration, Funding acquisition, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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