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ENHANCING URBAN WATER SUPPLY SYSTEMS RESILIENCE TO FLOODS IN WEST SUMATRA PROVINCE, INDONESIA: A FUZZY DELPHI APPROACH

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Abstract

Recurrent flood disasters in West Sumatra threaten the continuity of WSS services and the achievement of SDGs. However, WSS (Water Supply System) resilience frameworks that are adapted to local contexts remain limited. This study evaluated the urban WSS resilience framework by combining the FDM (Fuzzy Delphi Method) and Thematic analysis. FDM was chosen for its strong consensus with a small panel of experts, time and cost efficiency, and ability to capture subtle differences in judgment often missed by conventional statistics. Seventeen experts from Regional-Owned Enterprises (Badan Usaha Milik Daerah, BUMD) for Drinking Water, National Disaster Management Agency, Academics, the Ministry of Public Works, and local governments assessed 12 indicators grouped into four properties (procedural, structural, organizational, and complexity). Additional variables were extracted from expert comments using thematic analysis. The results explained that the properties with the highest consensus were procedural system and structural system (89.71%), followed by organizational framework (88.73%), and system complexity (84.74%), but the organizational framework indicator obtained the highest average level of agreement (90.15%) among the others. The four indicators with the highest agreement were the existence of a flood monitoring and early warning system, flood-resistant infrastructure design and construction, WSS infrastructure protection, and safety culture in organizations. Thematic analysis added ten variables, such as governmental recovery, crisis regulation and legislation implementation, and governance and policy transformation, which highlight the important role of central and local governments in enhancing resilience. This study provides recommendations to Drinking water BUMD in enhancing its resilience through a procedural system by preparing and implementing WSP (Water safety plan) and integrating its system into an EWS (Early warning system). Central and local governments, which hold mandatory responsibilities in WSS provision, can strengthen policies and strategies for risk management. This can be achieved through crisis regulation, legislation implementation, and governance and policy transformation.

Keywords:

Urban Water Supply System;
Floods;
Resilience;
Properties;
Fuzzy Delphi Method (FDM);
Thematic analysis.

1 Introduction

The level of flood vulnerability in Indonesia is very high. According to National Disaster Management Authority (*Badan Nasional Penanggulangan Bencana*, BNPB) data [1], 81.61% of regencies and cities in Indonesia are classified as high-risk areas for flooding. West Sumatra is one of the most flood-prone provinces, with all 19 cities and regencies at high risk of floods, and almost half of all disasters from 1904 to 2014 were floods [2]. Flood disasters can disrupt WSS infrastructure services and cause significant disruption to its components [3, 4], hindering the achievement of the SDGs' (Sustainable Development Goals) target related to access to adequate and safe drinking water. WSS is a critical infrastructure for society, and its disruptions can trigger effects that impact the economy, health, security, and government functions [4–6]. For instance, floods accompanied by landslides in

March 2024 affected the services of the Regional-Owned Enterprises (*Badan Usaha Milik Daerah,* BUMD) for Drinking Water in 10 regencies and cities in West Sumatra Province. The disaster damaged the WSS infrastructure, particularly the raw water unit, and halted the distribution of water to the community in several service areas. Upper-middle-income countries face significant challenges in managing flood losses. Rapidly developing infrastructure but low resilience results in high asset exposure to flood disasters.

Flood risks to the WSS are systemic and complex, arising from the interaction and interdependence of various socio-technical components [7–10]. To address systemic risks, disaster risk reduction and resilience must be integrated into national and regional policies and programs, especially in flood-prone areas, that also consider disaster risks and climate change [11, 12]. The sustainability approach is frequently employed with the aim of maintaining long-term balance [13, 14], but its implementation poses significant challenges due to the WSS operating within a VUCA (volatile, uncertain, complex, ambiguous) environment that necessitates strategic and coordinated socio-technical interventions [8]. Consequently, the resilience framework, which emphasizes the system's capacity to absorb, adapt, and transform in response to shocks [13, 14], is more suitably applied in disaster-prone regions such as West Sumatra. Davoudi et al. [13] also emphasized that the resilience approach is able to reveal structural issues more concretely. When discussing the concept of resilience, discussions about institutional vulnerability, governance limitations, and infrastructure vulnerability become sharper, where resilience encourages stakeholders to question the status quo, triggers more critical discussions about systemic change, and forces political discussions about the burdens and responsibilities of each stakeholder [13].

The resilience approach in dealing with disasters, such as floods, is becoming increasingly important, considering that currently the government and WSS organizations are faced with serious challenges such as adaptation to climate change, geopolitical constellation changes, the impact of economic decline, and massive cuts in public budgets in the infrastructure sector. This condition requires us to change our perspective and actions by looking for the root causes of the problem and reconsidering the relevance of current institutions and policies in ensuring the effectiveness of WSS services in Indonesia. Therefore, further studies are necessary to develop the WSS resilience concept and indicators that address the region's unique challenges to floods.

The application of the resilience concept in Indonesia, particularly in West Sumatra Province, faces obstacles due to limited research. Most studies on WSS focus on technical aspects and are conducted in developed countries, while similar studies in developing countries are minimal [15]. The available resilience assessment framework does not fully reflect local conditions. Researchers emphasize the need to adjust resilience indicators to be more contextual and effective [16, 17]. A qualitative approach based on expert opinion is more adaptive for assessing resilience, especially in uncertain disaster situations [18, 19]. However, the application of expert evaluation methods considering region-specific disaster characteristics remains limited.

This study aims to fill this gap by developing variables (properties and indicators) that explicitly address the need to improve WSS resilience to flooding in West Sumatra Province. Specifically, the objectives of this study are to assess the level of importance of resilience variables using the Fuzzy Delphi Method (FDM) and identify additional variables through qualitative expert insights using thematic analysis. FDM is a semi-quantitative method, integrating the expert consensus process of the Delphi method with Fuzzy set theory to represent and process the uncertainty inherent in expert judgments. A semi-quantitative method refers to an analytical approach that provides estimates of relative rather than precise numerical values. FDM proves relevant due to rising uncertainty, limited availability of reliable quantitative data, variations in panellists' perceptions that may be missed in conventional statistical analysis [19–22]. The findings of this study are intended to enrich the understanding of key resilience variables (properties and indicators) and offer practical insights to improve WSS resilience in flood-prone areas.

2 Methodology

2.1 Research design

Hypothetical variables, as shown in Table 1, were derived through conceptual analysis using the a Schwartz-Barcott and Kim's hybrid model, based on empirical sources such as government audit reports, field observations, and interviews with managers from the Padang City Regional Water Supply Company (One of BUMD for Drinking Water in West Sumatra Province) and experts from the Sumatra River Basin Center V, Ministry of Public Works. The resulting conceptual framework defines WSS resilience as the system's ability to maintain its function and structure during flood disturbances, supported by four internal properties to absorb shocks, adapt operations, and recover, namely: procedural systems (non-technical measures), structural systems (technical measures), system complexity (adaptive configurations), and organizational frameworks (institutional capacity). The indicators in this study are qualitatively measurable variables that represent specific aspects of the resilience properties.

Table 1: Hypothesis variables affecting WSS resilience to flood.

Properties	Indicators	Citation
Procedural system (A)	Clear Standard Operating Procedures (SOP) and manuals (A1) Comprehensive preparedness, emergency, and recovery (A2) The presence of policies and strategies for risk management (A3) The existence of a flood monitoring and early warning system (A4)	[7], [15], [23]–[31]
Structural system (B)	Flood-resistant infrastructure design and construction (B1) Flood-resistant materials and technology (B2) WSS Infrastructure Protection (B3)	[9], [19], [23]–[25], [31]–[35]
System's complexity (C)	Flexible system structure (C1) Flexible system procedure (C2)	[16], [19], [24], [26], [31], [32], [36]
Organizational framework (D)	Human resource capacity development programs (D1) Resource management (monetary, physical, technological, information) (D2) Safety culture in organizations (D3)	[6], [15], [20], [23], [27]–[30], [35], [37]

This study utilized a mixed-methods design, integrating the FDM (semi-quantitative) to validate hypothetical variables (4 properties and 12 indicators) and with thematic analysis (qualitative) to identify the additional variables affecting urban WSS resilience to floods. In this study, 20 experts were invited, with the criteria of having at least 10 years of executive experience, understanding the study area, and having expertise in the fields of resilience and/or risk management, WSS management, watershed management, and policies and regulations. According to the literature [38], the number of experts to evaluate and prioritize variables should be between 3 and 15 experts.

The questionnaire design that will be answered by the experts is a structured questionnaire with a 5-point Likert scale and short essay questions via Google Forms. The Likert scale is a psychometric and ordinal scale commonly used in surveys and questionnaires to measure attitudes, opinions, or perceptions. Data from the Likert scale were analyzed using a Likert-fuzzy approach, which allows researchers to detect subtle shifts in the panel's perspectives that may not be apparent through conventional statistical analysis, while essay responses were analyzed using thematic analysis methods. Figure 1 shows the stages of enhancing WSS resilience variables to floods.

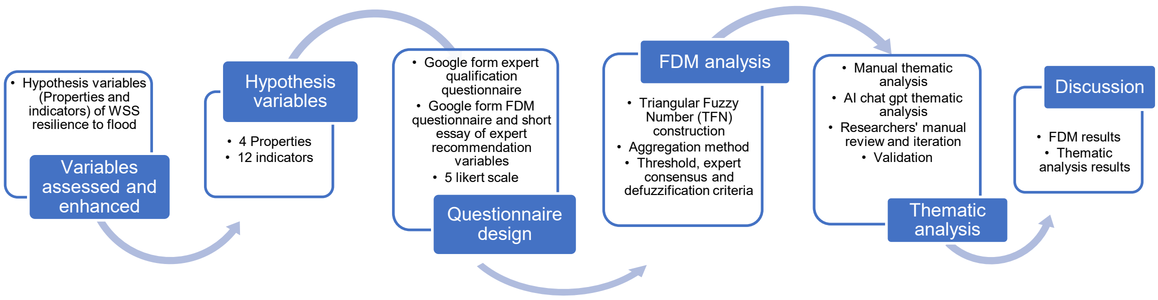

Fig. 1: Stages of enhancing WSS resilience variables.

2.2 Fuzzy Delphi Method (FDM)

The analysis of expert assessment results utilizes the Likert-fuzzy method, following the process outlined by Chang, Hsu and Chang [39] and Hasim et al. [40]:

1) Questionnaire design. Questionnaire development based on Hypothesis variables affecting WSS resilience to flood in Table 1. Five Likert scales and short questions were used via Google Forms to evaluate the importance level of variables. The Likert scale ranged from (1) very unimportant to (5) very important.

2) Triangular Fuzzy Number (TFN) construction

The conversion of the Likert scale into a fuzzy value is known as the Triangular Fuzzy Number (TFN) method (see Table 2). A fuzzy membership function is created for each Likert value. TFN uses a real number scale in the closed range of 0–1. Decision-makers find this function easy to use and calculate, and appropriate for representing decision problems dominated by subjective and uncertain information [21]. Incorporating fuzzy logic into the Likert method enables a more flexible analysis of responses, accommodating uncertainty or hesitancy in the experts' perception.

Table 2: TFN five-point Likert scale [21].

Likert scale	Level of importance	Fuzzy number
1	Very not important	(0, 0, 0,25)
2	Not important	(0, 0.25, 0.5)
3	Moderately important	(0.25, 0.5, 0,75)
4	Important	(0.5, 0.75, 1)
5	Very important	(0.75, 1, 1)

3) Aggregation method

The Likert-fuzzy method applies fuzzy operations to convert Likert scale responses into triangular fuzzy numbers (TFNs). The first step is to carry out fuzzy aggregation of the collected opinions. Each expert's opinion is expressed as a TFN (l, m, u). Aggregation is employed to merge the information provided by the respondents. The method for computing the fuzzy average of the experts' opinions is computed using the formula shown in equation (1).

$$F_{AVE} = \left(\frac{\sum l}{n}, \frac{\sum m}{n}, \frac{\sum u}{n}\right) \quad (1)$$

where:
F_{AVE} - The fuzzy average TFN of all experts' opinions
n - The total number of experts whose opinions were elicited.

4) Threshold, expert consensus and defuzzification criteria.

A statement or opinion that can be accepted through Likert-fuzzy analysis must fulfill three conditions. These conditions are necessary to reach a consensus conclusion among the experts:

• Threshold value. The first condition that must be met is the threshold value (d), Compute the threshold between two triangular fuzzy numbers (L, M, U) and ($l1, m1, u1$) using the formula (2)

$$\boldsymbol{d}\,(\mathrm{m,n}) = \sqrt[2]{\frac{1}{3}\left[(\mathrm{L}-\mathrm{l1})^2 + (\mathrm{M}-\mathrm{m1})^2 + (\mathrm{U}-\mathrm{u1})^2\right]} \quad (2)$$

where: $d\ (m,n) =$ the threshold distance between the triangular fuzzy numbers (TFNs) provided by expert m and expert n for the same item

For experts m and n, their TFNs are (L, M, U) and ($l1, m1, u1$)

Each expert's judgment is represented as a TFN score, which consists of three components: Lower (L) limit score of the assessment, Middle (M) score of the assessment, Upper (U) limit score of the assessment.

Table 3: Interpretation of threshold values (d).

Threshold values [d]	Interpretations
$\boldsymbol{d} \leq 0,2$	Indicator/item accepted
$\boldsymbol{d} > 0,2$	Indicator/item rejected

• Expert agreement percentage. The second condition to determine the expert agreement value is to ensure that the expert agreement percentage is > 75% based on Chang, Hsu, and Chang [39].

• Defuzzified score (A). The third condition ensures that the average fuzzy number's fuzzy score (A) value or defuzzification is greater than or equal to the median fuzzy number value. The median value of fuzzy numbers 0 and 1 is 0.5 [40, 41]. Determining the fuzzy score (A) aims to validate items, assess their level of importance and relevance, and identify the most significant items in the research context based on expert opinion. Fuzzy score (A) converts fuzzy values back to crisp values for a more straightforward interpretation. The fuzzy score value can be calculated using equation (3) when each expert's opinion is displayed as TFN (l, m, u). If the A value is less than 0.5, the item will be rejected because there is no expert agreement.

$$Amax = (L+M+U)/3 \quad (3)$$

The item will be rejected if the A value is less than 0.5 because it does not show expert agreement.

2.3 Thematic Analysis

The thematic analysis method was used to analyse the variable recommendations and expert responses. Zhang et al.[42] showed that method-aware prompt design, iteration, and manual analysis made ChatGPT a reliable tool in thematic analysis. The detailed thematic analysis method is as follows:

1) Researchers prepare a dataset of short essays from experts and sort the content to be analized by eliminating out-of-focus parts and dividing the content into units of analysis.

2) Thematic analysis by ChatGPT Plus Core Prompt Framework. The core prompt section includes:

• Task background

GPT Chat will analyze qualitative data from expert essay transcripts. The main objective is to identify codes and themes related to the question: “What codes and themes emerge from the transcripts of expert recommendation essays for improving the resilience of WSS to flood?”

• Task description and method

Use the thematic analysis method (Braun and Clarke) [43] through the following steps: familiarization (exploring initial meanings and ideas), initial codes (labeling text fragments), searching for themes (grouping codes), reviewing themes (checking cohesion and differences between themes), naming and defining themes (writing short narratives and scope for each theme).

• Processing rules

Work only on the text in the “Data esai” section below; Do not change the respondent's words when providing example quotes; Create a structured table: codes, brief descriptions, sample quotes, temporary themes; Once all codes are created, present a final list of themes with a 1-2 sentence explanation for each theme; If there are any inconsistencies or ambiguities, note “human review needed.”; Role play: “You are acting as a senior qualitative analyst.”

• Expected output format

Organise the results of the thematic analysis: present themes, supporting quotes, and theoretical discussions in a tabular format.

3) Researchers conducted a manual thematic analysis with the help of the QDA Miner Lite software application.

4) Result

The initial ChatGPT results were filtered and then optimised iteratively. Researchers conducted a final manual review before determining the “results of targeted missions.”

5) Validation

The results of the thematic analysis were tested through interviews with two experts from the Padang city’s Drinking water BUMD.

2.4 Utilizing of artificial intelligence (AI) assisted technology

Several researchers have utilized artificial intelligence (AI) to enhance the quality of their research. Goodwin et al. [44] employed Chat GPT (Open AI GPT-3.5) to enhance manual thematic analysis. Zhang et al. [42] studied the effectiveness of Chat GPT in improving the thematic analysis process. It provides a framework to improve the quality of thematic analysis and establish significant connections between AI and qualitative research. It provides a framework to bolster the caliber of thematic analysis and establish significant connections between AI and qualitative research. Building on the framework established by Zhang et al. [42]. The present study employs Open AI GPT o1 (advanced reasoning) to conduct a thematic analysis of textual data derived from anonymous interviews and questionnaire essay responses. The data processed with Open AI GPT o1 is utilized as a point of comparison for manual data analysis using QDA Miner Lite software.

2.5 Study area

This study was conducted in West Sumatra Province, Indonesia, which geographically lies between 0°54' N and 3°30' S latitude and 98°36' E and 101°53' E longitude. West Sumatra Province has experienced floods as the predominant disaster from 1904 to 2015, accounting for 47.49% of total events. The region is characterised by high levels of hazard, vulnerability, and risk, coupled with limited community capacity [2]. This has a significant impact on urban WSS services because the source and infrastructure of raw water are located in the upstream area of the river. According to the Financial and Development Supervisory Board performance report in 2024, no Drinking water BUMD in this province has implemented an asset management policy that adequately addresses the risk of operational failure. This contributes to the low coverage of piped network services, which reached only 26.94% in 2023.

Figure 2 shows the study location and performance of the Drinking Water BUMD based on the 2024 Financial and Development Supervisory Board performance report.

Identification of urban WSS in seven districts and cities in West Sumatra Province (Padang, Padang Panjang, Limapuluh Kota, Pasaman, Pesisir Selatan, Sijunjung, and Tanah Datar) by the Regional Settlement Infrastructure Center of West Sumatra, Ministry of Public Works and Housing in 2024, revealed significant vulnerabilities to flood impacts. The flash floods in Padang City on August 18, 2021, damaged the WSS intake of the Padang City Drinking Water Company, resulting in the water supply being cut off to three sub-districts and around 45,000 customers not receiving clean water. Flash floods in South Solok Regency on November 21, 2019, caused damage to the network, the Water Treatment Plant (WTP), and the intake. In March 2024, 10 regencies/cities in West Sumatra Province experienced flash floods accompanied by landslides. The most impacted areas were Padang City, Padang Pariaman Regency, and Pesisir Selatan. According to the Meteorological, Climatological, and Geophysical Agency, the region experiences above-normal annual rainfall. The flood that occurred on March 7, 2024, in Padang City resulted in significant damage to the Raw Water intake and transmission pipe with a diameter of 300 mm at the Lubuk Paraku WSS Unit, which is under the operation of the Padang Municipal Drinking Water Company.

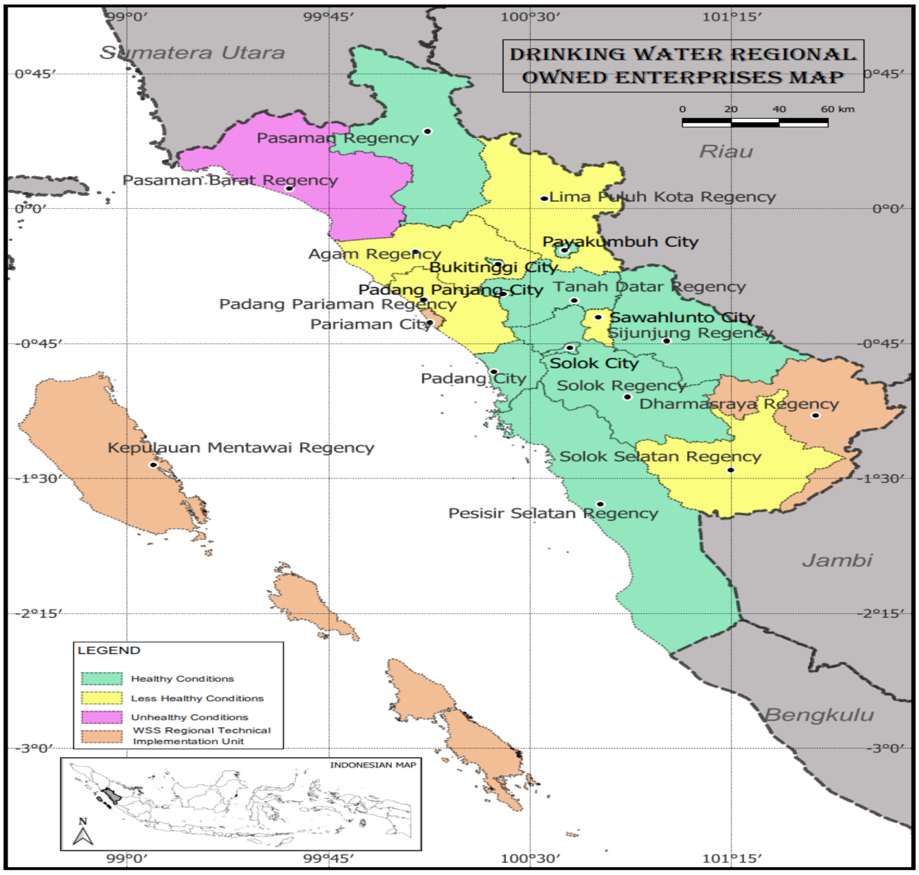

Fig. 2: Location of research in West Sumatra Province.

3 Results

3.1 Evaluation of expert qualification conclusion

At the beginning of the study, 20 experts were invited to complete two forms (expert qualification form and assessment form) via Google Forms. Three experts were excluded from the panel; two completed only the expert qualification form, and one completed only the WSS flood resilience variable assessment form. As a result, 17 experts participated in the study, yielding a positive expert coefficient value of 85%, which indicates that most experts actively engaged in the research. Panel size in Delphi does not depend on statistical power, but rather on group dynamics in reaching consensus [45]. Table 4 explains the expert's expertise qualifications at the preliminary assessment phase.

Table 4: Expert qualifications at the expert's assessment phase.

Expert	Information	Frequency
Educational background	Bachelor Master Doctoral	3 12 2
Experience related to the research topic	10-19 years 20-29 years ≥30 years	9 5 3
institution	Municipal Drinking Water Company National Disaster Management Authority Academics Consultant River Basin Organization of Sumatra V Local Public Works and Spacial Planning Local Development Planning Agency	5 2 3 1 2 2 2
Organizational services	Disaster management Central area National Disaster Management Academic services Consulting services in water resources and WSS Management services in water supply systems Water resources management services Public Works and Spatial Planning Local planning and development services	1 1 3 1 5 2 2 2
Number of Experts	17	

Seventeen experts evaluated their familiarity with resilience, risk management, WSS management, natural resource management, watershed management, and related policies and regulations. Understanding an expert's familiarity with the research topic is crucial for ensuring they have the relevant knowledge and experience for the evaluation. When most experts show a high level of familiarity, the validity of the study results is enhanced, as they are based on informed opinions. The researcher employed the Likert-fuzzy and expert judgment methods to evaluate experts' qualifications. The analysis is presented in Table 5.

Table 5: Expert's level of familiarity with the research subject.

Topics	Condition of TFNs		Condition of Defuzzification Process			Expert Familiarity/ Fuzzy Score [A]
	Threshold value $[d]$	Opinion similarity [%]	m1	m2	m3	
Resilience and/or risk management	0.14	74.60	0.44	0.69	0.91	0.68
WSS management	0.19	80.88	0.52	0.78	0.92	0.74
Watershed Management	0.12	81.31	0.57	0.82	0.97	0.79
Natural Resources Management	0.16	79.37	0.51	0.76	0.93	0.74
Policies and Regulations	0.13	82.32	0.59	0.84	0.97	0.80

The threshold value (d) of 0.2 indicates significant variation in expert familiarity levels. Diverse disciplines are essential for a comprehensive resilience concept. The study invited experts with varied understandings; for instance, some may specialize in watershed management but be less familiar with WSS management. A panel with heterogeneous expertise helps identify critical aspects that may be overlooked by a more focused panel [39].

The Fuzzy Score (A) reflects expert familiarity levels, with a value greater than 0.75 indicating strong familiarity. The expert familiarity value for resilience and/or risk management is 0.68, within the threshold of 0.5, likely due to resilience being a relatively new concept. The percentage of similarity of opinion measures how many experts provide similar assessments, with a value of 74.60%, indicating a low but acceptable level of agreement above the 70% convergence threshold. This suggests significant variation in experts' familiarity and interpretations of resilience. Overall, the participation of 17 experts reflects the convergence, understanding, and variation in familiarity with the research topics.

3.2 Resilience hypothesis variable assessment

In this chapter, expert consensus on the importance of the WSS resilience hypothesis variables (properties and indicators) is evaluated using FDM, while their essay responses are examined through thematic analysis.

3.2.1 Likert-fuzzy analysis result

Experts assess the agreement rating for the resilience hypothesis variables. The rating assessment uses a five-point Likert scale. In addition, experts can add properties and other indicators and provide comments or opinions according to their experience and knowledge. The Likert-fuzzy analysis can be seen in Table 6.

Table 6: Analysis of resilience properties assessment.

Properties	Condition of TFNs		Condition of Defuzzification Process			Fuzzy Score [A]	Experts Consensus	Ranking
	Threshold value [d]	Expert agreement [%]	m1	m2	m3			
A	0.04	89.71	0.72	0.97	1.00	0.90	Accept	1
B	0.04	89.71	0.72	0.97	1.00	0.90	Accept	1
C	0.16	84.74	0.60	0.85	0.94	0.80	Accept	3
D	0.06	88.73	0.71	0.96	1.00	0.89	Accept	2

Table 7: Assessment of Likert-fuzzy hypothesis indicators.

Indicators	Condition of TFNs		Condition of Defuzzification Process			Fuzzy Score [A]	Experts Consensus	Ranking
	Threshold value [d]	Expert agreement [%]	m1	m2	m3			
Procedural system (A) indicators:								
A1	0.06	88.73	0.71	0.96	1	0.89	Accept	3
A2	0.04	89.71	0.72	0.97	1	0.90	Accept	2
A3	0.04	89.71	0.72	0.97	1	0.90	Accept	2
A4	0.02	90.69	0.74	0.99	1	0.91	Accept	1
Mean	0.04	89.71	0.72	0.97	1.00	0.90		
Structural system (B) indicators:								
B1	0.02	90.69	0.74	0.99	1	0.91	Accept	1
B2	0.06	88.73	0.71	0.96	1	0.89	Accept	2
B3	0.02	90.69	0.74	0.99	1	0.91	Accept	1
Mean	0.03	90.04	0.73	0.98	1.00	0.90		
System's complexity (C) indicators:								
C1	0.16	85.77	0.62	0.87	0.94	0.81	Accept	1
C2	0.16	83.7	0.59	0.84	0.94	0.79	Accept	2
Mean	0.16	84.74	0.61	0.86	0.94	0.80		
Organizational framework (D) indicators:								
D1	0.04	89.71	0.72	0.97	1	0.9	Accept	2
D2	0.04	89.71	0.72	0.97	1	0.9	Accept	2
D3	0.02	90.69	0.74	0.99	1	0.91	Accept	1
Mean	0.03	90.15	0.73	0.98	1.00	0.90		

1) Procedural system (A)

The exceptionally low threshold value of d (0.04), coupled with an agreement level nearing 90% and a defuzzification score of 0.90, indicates a strong consensus that the Procedural system (A) is among the most critical properties for enhancing WSS resilience. For the system procedural indicator, the threshold value of $d \leq 0{,}2$ indicates a strong consensus among experts. All aggregated fuzzy scores exceed 0.5, and the highest average fuzzy score in this group is above 0.75, indicating that the level of importance of the system procedural indicator is very high. In addition, the percentage of expert agreement (Pi) for each system procedural indicator is also almost 90%, confirming the validity and consistency of their assessments. The results of this analysis firmly confirm and complement the concept of protocol-driven resilience by Francis and Amodeo [46] which is conceptual and normative. This finding provides empirical evidence that in the WSS resilience framework, experts also place protocols/procedures as the most crucial element. The integration of both strengthens the theoretical and practical basis that protocols/procedures (in the form of Clear Standard Operating Procedures (SOP) and manuals (A1), Comprehensive preparedness, emergency, and recovery (A2), The presence of policies and strategies for risk management (A3), The existence of flood monitoring and early warning system (A4)) are the main mechanisms of system resilience to disturbances.

2) Structural system (B)

Structural system (B) has identical threshold d value, agreement level, and defuzzification score with Procedural system (A), indicating that both are viewed as equal priorities in strengthening WSS resilience. Among the structural indicators, Flood-resistant infrastructure design and construction (B1) and WSS Infrastructure Protection (B3) rank the highest, with threshold d of 0.04, agreement level reaching 90.69%, and defuzzification score of 0.91. Meanwhile, Flood-resistant materials and technology (B2) indicator, although still meeting all consensus criteria, obtained slightly lower agreement level than B1 and B3. This is likely due to the diverse backgrounds of the experts, so that their perceptions of the effectiveness of materials and technologies in improving WSS resilience also vary, which causes a wider spread of assessments and increases the d value. In addition, another factor that may influence is the local conditions where only two Drinking Water BUMD in West Sumatra Province have met the Going Concern criteria according to the Financial and Development Supervisory Board performance report on 2024. This condition indicates that the implementation of indicator B2 may not yet be a priority or may not yet be possible in most areas. This is reinforced by the opinion of Expert 17, who emphasized the importance of cost-benefit analysis, considering that the implementation of advanced technology requires large investments.

3) System's complexity (C)

The system complexity property obtained the lowest consensus level compared to other properties, with a threshold value of d = 0.16 which is close to the threshold limit of 0.20, a relatively low level of agreement (84.74%), and a defuzzification score of A = 0.80 which is still in the acceptable category. This value reflects the diversity of views among experts. Two indicators of system complexity, the flexible system structure indicator (C1) and the flexible system procedure (C2), obtained a threshold value (d) of 0.16, indicating high variability. This may be due to differences in interpretation or ambiguity in the indicators.

Expert 2 highlighted the need for more precise WSS technical terminology to describe flexible system structure. Expert 7 suggested that structural system properties and complexity be combined into a new property, system reliability. Meanwhile, Expert 15 suggested that complexity indicators be more appropriately included in structural and procedural attributes. Expert 16 acknowledged that these indicators do reflect the characteristics of the WSS system, but in his opinion do not provide a direct contribution to increasing resilience. In addition, Expert 4 considered that the indicators used were still too broad and too few; they should be made more specific and more numerous, so as to allow for sharper priority ranking. These collective inputs highlight the need to refine the variable structure, property and indicator levels, to ensure that the developed framework is clearer, more accurate, and more relevant to real conditions in the field.

4) Organizational framework (D)

Although the value of the organizational framework property (D) is slightly lower than the A and B properties (d = 0.06; agreement = 88.73%; A = 0.89), its value is still far above the FDM consensus threshold. Interestingly, the average agreement on indicators Organizational framework D actually reached 90.15%, the highest among all properties. This is likely because, when assessing the organizational framework property (D), some experts interpreted it abstractly, resulting in a slightly lower score but showing high agreement when the indicator was described concretely. This finding confirms that strengthening governance (human resource capacity development programs (D1), resource management (monetary, physical, technological, and information) (D2), and safety culture in organizations (D3)) is very important to ensure that the implementation of the procedural system (A) and structural system (B) properties truly contributes to increasing WSS resilience. This finding supports McClymont et al. (2020) [16] view that effective flood resilience requires an integrated approach beyond technical solutions, incorporating political and social aspects.

3.2.2 Thematic Analysis

Seventeen experts contributed brief essays offering feedback and recommendations on the resilience variable hypothesis. This aimed to validate their perspectives on the Likert scale responses and provide deeper insights into enhancing resilience variables. Thematic analysis was used to extract themes from the experts' comments. The results of the thematic analysis identified 12 important variables to improve WSS resilience, which were then consulted with two experts from Padang city's Drinking water BUMD. Two variables were considered irrelevant and were removed based on consultation. Qualified construction service providers are considered to have been reflected in the Human resource capacity development programs (D1) indicator, while redundancy capacity is considered to have been represented in the flexible response variable, besides its implementation is not yet relevant and realistic because currently to meet operational costs, maintenance, system updates and WSS development alone, WSS is still not optimal due to budget constraints. The ten variables under consideration are explained as follows:

1) Contingency plan

Expert 2 stated: "There is a need for contingency plan indicators. These indicators should be formulated collectively and activated during emergencies, serving as the operational plan for the WSS in the event of floods. The contingency plan outlines agreed scenarios and objectives, establishes technical and managerial actions, and defines the response and mobilization of resources as decided by the involved agencies." Expert 2 also explained: "The government's preparedness involves emergency command management focusing on the coordination of teams, resources, and operational steps to ensure a rapid and effective response to incidents that could disrupt safety and operations."

2) Comprehensive feasibility studies

Experts explain that transitioning to the resilience-based approach requires realistic considerations through comprehensive feasibility studies. Expert 3 states: "The system's reserve capacity is influenced by budget availability. For example, when it comes to raw water pumps, if we need to replace them, there are no funds, let alone reserves. The key lies in financing. Ideally, these systems would have backups. We've repeatedly asked for support, but there has been no execution. Disaster-resilient WSS planning often requires a substantial budget, so a feasibility study must be conducted for every Detailed Engineering Design (DED) to ensure the mitigation strategy is operationally and financially viable. Relying solely on risk analysis to guide decision-making can lead to suboptimal policies, as it fails to account for budget constraints and investment efficiency." Expert 7 adds: "The current system design remains risky because, to transport water by gravity, the transmission pipes follow the contour where the required head exists; however, this route is prone to flooding. If the transmission pipes are elevated at the intake point, pumps will be needed, which entails high operational and electricity costs. Are communities prepared for a tariff increase, or would they prefer to accept potential water outages due to flooding?". The comprehensive feasibility studies variable is in line with the study of Al-Juboori et.al. [47]. They assess the success of WSS through technical-economic feasibility, referring to a study in India where technical feasibility is the most significant factor in operation and maintenance.

3) Crisis response budget

Expert 17 states: "Asset management remains preventive due to budget limitations. The Full Cost Recovery (FCR) framework does not accommodate rehabilitation costs and Non-Revenue Water (NRW). The current tariff structure equalizes the basic tariff." Expert 9 explains: "Some of the intake structures and transmission pipes used by the Municipal Drinking Water Company are typically assets owned by the Sumatra River Basin Center V, under the Directorate General of Water Resources, Ministry of Public Works and Public Housing. The Municipal Drinking Water Company only utilizes these assets. If these assets incur complex damages, the company cannot fully address them due to a limited budget, resulting in suboptimal rehabilitation efforts. Funding proposals submitted to the River Basin Center through operational and maintenance (O&M) funds are not immediately prioritized, as O&M allocations are generally assigned to pre-determined activities. Therefore, a proactive funding model is needed for the Municipal Drinking Water Company that can be readily used during a disaster." As a result, a Crisis Response Budget is essential, as emphasized by Expert 6: "To meet the criteria for resilient structural attributes, as outlined in the indicators above, adequate funding is required, supported by appropriate technological innovations."

4) Governmental recovery

The government allocates emergency disaster funds based on Disaster Management Agency Regulation No. 4 of 2020 on the Use of Ready-to-Use Funds. However, budgeting regulations for rehabilitation and reconstruction remain unclear, as noted by Expert 8: "When damage occurs to WSS units, repair budgets from Operational and Maintenance (OM) funds are often insufficient, causing proposals from Municipal Drinking Water Companies to be deferred to the following fiscal year. Although regulations allow rehabilitation and reconstruction budgets under the Ministry of Public Works and Housing Regulation No. 994/KPTS/M/2016 on the Disaster Management Task Force, the bureaucratic procedures are overly complex."

Experience from past disasters has promoted a shift towards proactive rather than reactive approaches [6]. However, current funding conditions remain reactive, as highlighted by Expert 14: "The March 2024 flood impacted six Municipal Drinking Water Companies in West Sumatra Province, significantly affecting public services. However, recovery efforts were hampered by financial constraints. Neither local governments nor Municipal Drinking Water Companies have permanent recovery budgets. The Regional Settlement Infrastructure Center, responsible for implementing Government Regulation No. 122 of 2015 on the Water Supply System, manages special WSS projects, including disaster response. However, when local governments submit repair proposals, the Regional Settlement Infrastructure Center cannot immediately allocate funding, as post-disaster rehabilitation procedures are not included within the Regional Settlement Infrastructure Center's core duties and functions." In high-income countries, governments typically cover part of the post-disaster costs through public revenue from taxes, while local authorities manage the financing of recovery efforts [6].

5) Data acquisition and monitoring system (DAMS)

DAMS is designed to collect, monitor, and manage data in real-time from several WSS (Water Supply System) units. Expert 2 argues: “The availability of a flood monitoring system integrated with the existing disaster monitoring system within the Municipal Drinking Water Company and relevant authorities aims to detect potential flood threats that may arise.” Expert 9 adds: “The prevalence of manual systems hinders the detection process for damage points.” DAMS can enhance operational resilience through early detection, reducing downtime, and enabling fast, data-driven decision-making, thereby improving restorative capabilities [15], [28], [30], [37].

6) Crisis regulation and legislation implementation

Existing regulations can be implemented consistently if an audit of crisis regulation and legislation implementation is conducted. Expert 3 clearly states: “Once all stakeholders agree upon flood and emergency response procedures, the key lies in how consistently they are executed, such as the timeframe between the disaster occurrence and the initiation of emergency actions, as well as the budget allocated. Oversight of the implementation of regulations and SOPs is essential.”

7) System renewal and maintenance

System renewal is necessary, as highlighted by Expert 9: “Aging assets are more vulnerable to disasters. The Municipal Drinking Water Company faces budget constraints in renewing systems because it still relies on basic tariffs.” Expert 1 also emphasizes: “Regular maintenance, system upgrades, and repair budgets need to be prioritized by the Municipal Drinking Water Company, local governments, and the central government to ensure the sustainability of public services.”

8) Operation, maintenance, renewal funds

Expert 15 argues: “Central government programs often come from foreign aid funds aimed at developing new WSS infrastructure, whereas the programs needed by the Municipal Drinking Water Company focus more on replacing aging assets, reducing leakage, or enhancing institutional capacity and human resource competence.” This view aligns with Expert 9’s statement: “Central government programs prioritize building new systems rather than funding the replacement of aging infrastructure. The condition of the intake points and transmission systems increases their vulnerability to flood hazards.” Expert 1 adds: “Based on the Actual operation and maintenance needs data from several districts and cities, WSS intake points and transmission networks have suffered significant damage from flooding, exacerbated by the deterioration of aging infrastructure.”

9) Flexible response

Flexibility is the ability of organizations and systems to maintain smooth operations and respond to unexpected disruptions quickly and efficiently [31]. Expert 14 explains: “The system design and operations should be as flexible as possible so that water can be distributed normally during a disaster.” Expert 17 adds: “A flexible system design is essential, but its implementation incurs costs due to advanced technologies. Implementing a flexible system design requires a cost-benefit analysis evaluation.”

The views of several experts on the three structural system indicators suggest that these indicators have not covered key aspects of the system’s structural properties. Aspects such as the availability of reserves, alternative sources, and interconnections between systems are still not represented. Expert 15 suggested: “It is necessary to consider using backup components in system design, enabling the system to remain operational if one component fails. This approach enhances reliability and facilitates recovery when disruptions occur. System protection is also an indicator that should be taken into account.” Expert 14 also emphasized: “Interconnection and interdependence are key factors in the system’s adaptation during changes in interactions caused by flooding.”

10) Governance and policy transformation

Expert 7 explains: “The Municipal Drinking Water Company has realistically calculated its business plan for the next five years, including the state and local government budgets that can be utilized. The local government has included the planned budget allocation in the WSS Master Plan’s documents, outlining the local government budget to be absorbed, but these plans have not been realized. Our Municipal Drinking Water Company has a Regional Regulation on capital participation worth 150 billion IDR, and the local government has committed to financing it, but the execution has not materialized. The only capital participation that has been implemented is limited to the Low-income household grant program. This may be because the local government assumes that the Municipal Drinking Water Company has achieved FCR. The company’s FCR is insufficient to cover rehabilitation costs, operations, and NRW. If we outline the rehabilitation needs, including pumps that need to be replaced, the company has not yet achieved FCR and should receive subsidies according to government regulations. Therefore, strict policy enforcement is necessary to ensure that the sustainability of the Municipal Drinking Water Company’s services to the public remains uninterrupted.”

Expert 3 explains how the Municipal Drinking Water Company is not independent in making policies: “The limited number of human resources is a challenge in enhancing the resilience of WSS. A shared vision and mission between the Municipal Drinking Water Company and the capital owner is necessary, as the company’s policies fully depend on the capital owner’s authority.” The World Bank (2021)[48] also noted that the limited autonomy of Drinking Water BUMDs, due to local government intervention, especially in keeping tariffs low, constrains the availability of funds for system maintenance and improvement. Resilience, in the context of governance and policy transformation, plays a role in modernizing the organizational structure of the Municipal Drinking Water Company and the government, improving decision-making processes, and enhancing inter-agency coordination [49]. Governance transformation will strengthen the company’s ability to respond to emergencies and implement infrastructure improvement programs without obstructive bureaucracy.

3.3 Discussion

The highest level of acceptance of resilience property indicators based on the results of the FDM analysis is the indicator of the existence of flood monitoring and early warning system (A4), flood-resistant infrastructure design and construction (B1), WSS infrastructure protection (B3) and safety culture in organizations (D3). These results are consistent with the findings of additional variables from the thematic analysis of the experts' brief responses. For example, indicator A4 is explicitly supported by an additional variable in the form of the existence of a Data acquisition and monitoring system (DAMS), because the availability of real-time data is an important component for a rapid response to flood disasters.

Indicator B1, namely the design and construction of flood-resistant infrastructure, is supported by the additional variable of comprehensive feasibility studies. The emphasis on this feasibility study is important to ensure that the design of infrastructure that is resistant to flood disasters is also supported by technical, financial, and human resource capabilities in its implementation. Indicator B3, namely the protection of WSS infrastructure, is supported by the variable of system renewal and maintenance and the variable of operational, maintenance, and renewal funds. These variables emphasize that infrastructure resilience to flooding cannot be separated from the availability of budget and continuous system maintenance and renewal. The indicator of Safety culture in organizations (indicator D3) is strengthened by the additional variable of flexible response capability. This variable offers the view that organizations that have a strong safety culture tend to be more adaptive and able to adjust quickly to changing conditions, especially in emergency situations.

Other indicators such as Comprehensive preparedness, emergency, and recovery (A2) are supported by the variables of contingency plans, crisis response budgets, and government recovery support. This emphasizes that disaster preparedness does not only depend on technical readiness but also on institutional readiness and government support. The presence of policies and strategies for risk management (indicator A3) is also strengthened by additional variables, namely crisis regulation , legislation implementation and governance and policy transformation. This finding is in line with Gibson et al. [11] who stated that transformative disaster risk management (DRM) occurs when a disaster drives systemic changes in governance, goals, and behavior, going beyond conventional strategies.

These findings indicate that the FDM consensus results, which place the Organizational Framework (D) as the indicator with the highest average expert agreement, are in line with the thematic analysis that emphasizes the role of institutions in WSS resilience. The thematic analysis also highlights the importance of policy transformation and the active role of the government in strengthening the governance of drinking water BUMDs to deal with disasters in West Sumatra, including institutional arrangements, regulations, and budget support. This idea aligns with Shaw's (2012)[17] view, which states that transformation at the local level can be achieved through changes in governance norms, utilization of available capacities, and the creation of institutions that support the learning process. This study’s emphasis on governance aligns with Zhou et al. [50], [51] underscoring the importance of soft resilience (institutional, economic, and environmental) over technical measures, particularly in disaster prevention. They found that rural WSS systems often lack operational funds, making institutional approaches more practical and adaptable than costly technical solutions. In contrast, Sweya et al. (2020)[26] focus on technical aspects, likely reflecting differing local needs and contexts.

Based on the resilience framework testing and identification of 10 additional variables from thematic analysis, this study proposes a number of strategic recommendations to strengthen WSS resilience in West Sumatra Province. Increasing resilience through procedural system properties can be done through the implementation of a clear SOP and manual (A1) and a flood monitoring and early warning system (EWS) (A4). Drinking Water BUMD needs to be integrated into the flood hazard EWS system. The involvement of Drinking Water BUMD in the EWS allows for a fast, precise, and efficient threat response. The presence of policies and strategies for risk management (A3) can be achieved by implementing the WSP (Water Safety Plan) document, which systematically covers three main components: water sources, operators, and consumers. WSP contributes to the IWRM (Integrated Water Resources Management) approach, thereby protecting the system from technical disruptions and strengthening the capacity of local governments in ensuring the sustainability, quality, quantity, and affordability of safe raw water sources.

To strengthen structural system properties, Drinking Water BUMD can adopt flood-resistant infrastructure design and construction (B1), WSS infrastructure protection (B3), and flood-resistant methods and technologies (B2) by referring to technical guidelines such as SNI (Indonesian National Standard) 7509:2011. This document is the main reference in designing or updating the WSS infrastructure. In addition, the implementation of low-cost smart structures such as flexible pipe connections with sensors can improve the network's ability to adapt in real time to flood disturbances. These smart structural elements have been proven to increase robustness, responsiveness, and adaptability, and accelerate the recovery of post-disaster infrastructure[52]. Increasing the resilience of the structural system property also needs to apply comprehensive feasibility studies, such as cost-benefit analysis, to assess whether the cost of adaptation investment is comparable to the potential losses due to disasters. The organizational framework property can be improved through human resource (D1), resource management (D2) and safety culture (D3) by integrating it into a business continuity plan that considers disaster scenarios and climate change. Government and Drinking water BUMD must integrate planning, budgeting, and monitoring to ensure that resilience interventions is clearly reflected in resource allocation and clearly implemented.

The central and local governments have a crucial role in strengthening WSS resilience through the Comprehensive Preparedness, Emergency, and Recovery (A2) strategy, including contingency plans and governmental recovery as stipulated in BNPB Regulation No. 2 of 2023. In addition, support in the form of accurate and coordinated risk mapping is very important, referring to the Regulation of the Head of BNPB No. 2 of 2012. To strengthen policies and strategies for risk management (A3), this can be achieved through crisis regulation, legislation implementation, and governance and policy transformation. Although Indonesia already has a number of regulations related to drinking water and disasters, there are still important gaps that need to be addressed immediately so that the drinking water system is more resilient to disasters. For example, the unavailability of implementing regulations after the amendment to the Water Resources Law and the absence of clear technical regulations regarding the post-disaster WSS infrastructure recovery process, which causes delays in WSS infrastructure repairs. Transformation of the financing scheme is also needed for the sustainability of the drinking water sector. Reforming the management of Drinking Water BUMD is also an important agenda, especially to reduce the dominance and intervention of power holders in operational decisions. This research redefines the resilience framework as the internal and external capacities of a system that underlie the system's ability to maintain function, absorb disturbances, adapt, recover, and transform.

Based on the redefined resilience framework, thematic analysis enhanced and refined the framework by identifying ten additional variables highlighting the strategic role of local and central governments as regulators. So that the framework’s attention is no longer only focused on the technical and institutional aspects of Drinking water BUMD, but also on administrative and policy aspects. However, these variables are still additional descriptive in nature and have not been systematically integrated into the FDM indicator structure, so their conceptual and functional validity require further testing. In addition, the homogeneity of the expert panel, all from West Sumatra Province, can create contextual bias and ‘blind spots’ on institutional issues that may not be relevant in other regions. Therefore, the implementation of this framework in other provinces requires further validation.

4 Conclusion

This study aims to fill the gap in the study of WSS resilience to flooding in West Sumatra Province by improving resilience variables consisting of properties and indicators that are relevant to the local context. Using a semi-quantitative approach through the FDM and a qualitative approach based on thematic analysis, this study evaluates initial indicators while identifying additional variables based on expert opinions. The findings of the study show consistency between the results of FDM and thematic analysis and emphasize the importance of the Organizational Framework (D) indicators as a foundation in strengthening WSS resilience. Experts also emphasize the need for policy transformation and the active role of the government in strengthening the governance of drinking water BUMDs. In practice, the resulting variables can be used as references by stakeholders, especially the central and regional governments and drinking water BUMDs, in designing policies and strategies to improve the resilience of drinking water services to flood threats. From a theoretical perspective, this study contributes to the development of literature by proposing a WSS resilience framework that integrates procedural, structural, and organizational frameworks, and the role of the government in the context of flood disasters in West Sumatra. However, although the thematic analysis successfully identified ten additional variables, their relationship to the twelve initial indicators of FDM results has not been presented conceptually. Therefore, further research needs to integrate these ten variables into the existing resilience framework, as well as refine and revalidate the resilience framework using conceptual analysis methods such as Schwartz-Barcott and Kim's hybrid model. Furthermore, filtering the level of importance of variables can be done with FDM.

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