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Socio-hydrogeological approach for strengthening groundwater management (case study of the Brantas-Metro Groundwater Basin, Malang, East Java Province, Indonesia)

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Groundwater sustainability in rapidly developing regions is increasingly threatened by over-extraction, land-use conversion, and limited public engagement in water governance. Socio-hydrogeology offers a multidisciplinary framework for understanding the reciprocal interactions between human behavior and groundwater conditions; however, its application remains limited, particularly in contexts where user and non-user groundwater group coexist. This study investigates the socio-hydrogeological factors shaping groundwater management in the Brantas–Metro Groundwater Basin, East Java, Indonesia—an area experiencing severe aquifer stress. A mixed-methods survey of respondents was conducted using a validated and reliable questionnaire representing six dimensions of socio-hydrogeology. Principal Component Analysis (PCA) was applied to identify the dominant latent factors influencing community responses. Three key variables emerged: Community Awareness, Community Participation, and the Ability to Accept and Adapt to Information, Technology, and Disaster Risks. The PCA results highlight six principal socio-hydrogeological factors: (1) perceived impacts of over-pumping, (2) the importance of groundwater information, (3) effectiveness of groundwater information dissemination, (4) willingness to participate, (5) recognition of management ineffectiveness, and (6) the need for hydrogeologist involvement. Notably, groundwater users demonstrated higher self-imposed conservation behaviors, whereas non-users relied more on external institutional support. Despite good conceptual understanding of groundwater issues, both groups exhibited reluctance to participate in management programs, revealing a persistent knowledge-action gap. The findings underscore the need for strengthened participatory governance, targeted information diffusion, and expert-supported community engagement to enhance groundwater resilience in stressed basins.

KEYWORDS

socio-hydrogeology, hydrogeology, groundwater management, community awareness, community participation

1 Introduction

Everybody has the basic human right to clean water and sanitation. Understanding this, Sustainable Development Goal 6 specifically focuses on access to clean water and sanitation, including that from groundwater resources. The accomplishment of the clean water and sanitation objective will facilitate the achievement of other SDG objectives, including the enhancement of the quality of human life (SDG 3), reduced hunger (SDG 1), and poverty (SDG 2). Water can be sourced from rainwater, lakes, groundwater, and rivers (Yuan et al., 2022). Groundwater is the main available water source, triggered by its commonality (Foster et al., 2013; Cantonati et al., 2020). However, population growth and a variety of human activities have put groundwater resources under considerable stress (Bierkens and Wada, 2019). Such pressure can cause the depletion of groundwater and the loss of water quality (Jia et al., 2019; Jain et al., 2021).

Groundwater sustainability is important to ensure the availability of clean water. Groundwater sustainability is becoming increasingly challenging due to the infiltration of pollutants into groundwater (Ouedraogo and Vanclooster, 2016; Muhib et al., 2023) and the over-extraction of groundwater resulting from substantial human activity (Mukherjee et al., 2018; Jia et al., 2019; Jain et al., 2021). While groundwater management approach were well understood by the community in Central Arizona, unwillingness to act on these approach limited the efficacy of conservation efforts, thus necessitating the involvement of hydrogeologists and government agencies (Bernat et al., 2023). Therefore, enhanced management of groundwater resources is essential to ensure their long-term sustainability.

Previous research has found failures in groundwater management (Molle et al., 2018; Nabavi, 2018; Rodríguez-Escales et al., 2018; Augustsson et al., 2020; Mianabadi et al., 2020; Bostic et al., 2023). Systematic and continuous failures potentially lead to water shortages. The impacts will be increasingly felt, especially in areas where groundwater is the primary source (Mianabadi et al., 2020). Facts from various places indicate that groundwater management is largely state-centered governance. Such management proves to be ineffective (Molle and Closas, 2019). The causes are weak monitoring and insufficient strengthening of management by the state/government. Whereas groundwater management should ideally be based on community-centered management (Molle et al., 2018). The social impacts of failed groundwater management include failure of rural domestic water supplies, increased costs for agricultural and industrial water provision, and hindering regional development (Gailey et al., 2022; Bostic et al., 2023). Research in Iran mentions that groundwater management failure occurs due to mistrust between local communities and policymakers, resulting in low public participation. Furthermore, communities also exhibit a lack of social learning experiences in groundwater management. This indicates the crucial importance of groundwater co-management (Nabavi, 2018). Research in the Mediterranean Basin recharge areas (Portugal, Spain, Italy, Malta, and Israel) shows that non-technical aspects are more critical than technical aspects in groundwater management. These non-technical aspects play a role in mitigating management risks. Non-technical aspects include legal constraints, economic conditions, social conditions, governance, and the evolution of issues related to groundwater quantity and quality (Rodríguez-Escales et al., 2018). Meanwhile, groundwater management failures occur more frequently in shallow groundwater, for instance in the San Joaquin Valley, California. Well owners continue to extract water from their wells, leading to increasingly deeper groundwater wells (Bostic et al., 2023). This highlights the need for greater attention to human aspects as a social factor in groundwater management.

Groundwater is part of the co-evolution of the water cycle and humanity, which means groundwater management must be a multidisciplinary endeavor (Hossain and Mertig, 2020). An interdisciplinary framework focused on human-water interactions, termed socio-hydrology, has been widely used to study human-flood interactions, socio-ecological transformations, and water shortages (Di Baldassarre et al., 2013; Han et al., 2017; Hossain and Mertig, 2020; Khadim et al., 2023). Although socio-hydrology offers significant insights, additional research is warranted to comprehensively address critical groundwater challenges, with particular attention to variations in infiltration and their subsequent effects on agricultural irrigation resources. Community reluctance to engage in groundwater management initiatives, despite abundant local understanding of groundwater, calls for active collaboration with both hydrogeologists and government agencies for effective local management (Hund et al., 2018; Oshun et al., 2021; Khadim et al., 2023).

This study defines groundwater as water extracted from below the ground surface by shallow dug wells or drilled wells. Rainwater infiltrates the earth below the surface, resulting in the formation of groundwater. Hydrogeologically, groundwater is stored in certain geological structures and materials referred to as aquifers (Jena et al., 2020). Groundwater is extracted from wells located on privately owned land or public/village property. Groundwater is cooperatively utilized by members of a groundwater user group. There are also non-groundwater users who do not utilize groundwater. Both groups established a community residing in the Brantas-Metro Groundwater Basin region of Malang.

The community may function either as an individual entity or as a collective, facilitating the exchange of information which impacts groundwater dynamics (Pouladi et al., 2019). The role of the community member as an individual considers factors such as population, gender, type of occupation, education level, and their activities (Pouladi et al., 2019; Re et al., 2021b; Calliera and Capri, 2022). The community member acts as a stakeholder group agent within its context (Pouladi et al., 2019; Carrión-Mero et al., 2021). Their actions are influenced by regulations from customary law or local government, agreements among community members, and their perceptions of groundwater (Carrión-Mero et al., 2021; He and James, 2021). Generally, public perception determines their active involvement in groundwater management, whether as users, stakeholders, or academics (Limaye, 2017; de Lafaye Micheaux and Jenia, 2021). In contrast to the previous research, this study divided the community into groundwater user groups and non-groundwater user groups, which did not include scientists/academics in the research.

The community also has the ability to identify the condition of every type of water they use, for example, the type of water, the amount of water used, and its quality (Pham et al., 2023). If there are changes in water conditions, for instance, during a disaster, the community generally seeks information, finds alternatives, and adapts to ensure the availability of potable water. Communities with lower education and low-income face higher barriers in their ability to receive and adapt to information, technology, and disaster risks (Limaye, 2017). This is also one of the considerations in this research.

Social factors in the wider community are also related to regulation and administration. These two aspects contain explanations, problem identification, technical rules, and financial assistance to the groups or communities (Limaye, 2017; Rodríguez-Escales et al., 2018). Official regulations by local/national governments and customary/local laws are also part of groundwater management variables (de Lafaye Micheaux and Jenia, 2021; Gailey et al., 2022). Groundwater management divides community into user groups and managing group (Rahimi-Feyzabad et al., 2022; Pham et al., 2023). Groundwater user groups are individuals who actually extract and use groundwater to support their activities. Besides user groups, there are managing groups. Managing groups are individuals/institutions who carry out processes of cooperation and communication in managing groundwater (Rahimi-Feyzabad et al., 2022). They also perform problem identification, problem-solving, and rule-setting processes (Bernat et al., 2023). Managing groups functioning as policymakers/government tend to engage in groundwater conservation (Rahimi-Feyzabad et al., 2022). In this study, it did not consider groundwater user groups and managing Groups, but groundwater user groups and non-groundwater user groups.

The community in this study is an individual living in Brantas-Metro Groundwater Basin, Malang, East Java Province, Indonesia. The community consists of groundwater user groups and non-groundwater user groups. This distinguishes current study from past studies. Groundwater user groups are individuals who actually extract and use groundwater to support their everyday activities. Groundwater is primarily used for washing, cooking, drinking, and other activities such as gardening, agriculture, service businesses, and industry. Groundwater user groups have specific behaviors regarding groundwater use. Research in Ca Mau explains that groundwater user behavior is determined by awareness of groundwater use, knowledge and information obtained about groundwater, ownership of water sources/wells, and the cost/price of groundwater (Pham et al., 2023). Furthermore, research in Vietnam also explains that factors such as water price control, increased awareness of groundwater use, and dissemination of hydrogeological investigations of groundwater are the most important aspects of groundwater management (Muenratch and Nguyen, 2023). In contrast to the Groundwater user group, non-groundwater user groups are individuals who do not take groundwater within the Brantas-Metro Groundwater Basin area, but they also live in the same area. Both Groundwater user groups and non-groundwater user groups do not include scientists or academics living in the region.

Socio-hydrogeology incorporates both social and hydrogeological factors, presenting an approach for managing groundwater sustainably (Re, 2015; Limaye, 2017; Hynds et al., 2018a; Hynds et al., 2018b). Originally introduced by Re (2015) this focuses on: (1) understanding human impacts on groundwater bodies; (2) the social impacts on human needs from the changes in groundwater quality and quantity; (3) the interactions between stakeholders in groundwater management; (4) how hydrogeological knowledge is used effectively; (5) how scientific knowledge closes the gap between questions and answers; (6) scientist and stakeholders' knowledge sharing. Emphasizing, however, the insight that the community has on the concepts of groundwater management, Re (2015) notes their unwillingness to engage in management programs. Such process requires the cooperation of hydrogeologists, governmental entities and community members for a proper and sustainable management of groundwater. The community in the Brantas-Metro Groundwater Basin relies exclusively on groundwater for its water supply. All requirements are entirely met by groundwater. This condition aligns with the prior idea of socio-hydrogeology. This research aims to determine the factors influencing groundwater management in the Brantas-Metro Groundwater Basin using socio-hydrogeological approach. Compared to previous research, there is a practical-knowledge gap with the current study. Previous studies did not fully utilize the socio-hydrogeological approach across all 6 aspects/foci. Additionally, they did not apply this approach to groundwater user groups and non-groundwater user groups. Thus, this research will provide new insights into the implementation of the socio-hydrogeology approach in sustainable groundwater management.

2 Methods

2.1 Research area

The research area is located in the Brantas-Metro Groundwater Basin, East Java Province, Indonesia, based on the Directorate of Environmental Geology (1984) (Figure 1). This basin, which includes the Malang Region, is under considerable stress from excessive groundwater extraction (Santoso and Nurumudin, 2020). This pressure results from the reduction of water catchment areas, which occurs when green areas such as forests and plantations are converted into recreational spaces for tourism or residential development (Atasa et al., 2022).

The heavy stress of groundwater resources caused by the increasing population highlights a vital requirement of researching the interaction between human activities and groundwater systems. Observation results indicate that community reliance on well water leads to a reduction in its availability. Wells are no longer used because they have relatively little water available (Figure 2). Consequently, the community has to seek other sources by subscribing to water from government-owned or local community-owned water distribution networks. Water networks owned by local community organizations generally involve establishing pipe distribution channels originating from springs, especially in villages located on the slopes of Kawi Volcano (Figure 3). Village communities in lowland areas near industrial and service zones generally switch to government-owned water distribution networks. To obtain this water, residents are required to pay a certain tariff. This is certainly different from using water from their own groundwater wells, which does not incur any cost. This condition impacts the increase in water costs for every household. Furthermore, the high-water demand has led to the drying up of several springs located in the Kawi Volcano Valley (Figure 4). The defunct springs subsequently cause irrigation channels to dry up, which can disrupt agriculture, especially during the dry season (Figure 5).

Currently, the upstream (western part) of the research location is a water catchment area, protected forest, community plantations, and agriculture, while the downstream (eastern and southern part) of the research location comprises agricultural areas, settlements, and industries. The eastern and southern parts of the research area are designated for urban, residential, and industrial development based on Regional Regulation of East Java Province Number 10 of 2023 concerning Spatial Planning of East Java Province 2023–2043. This

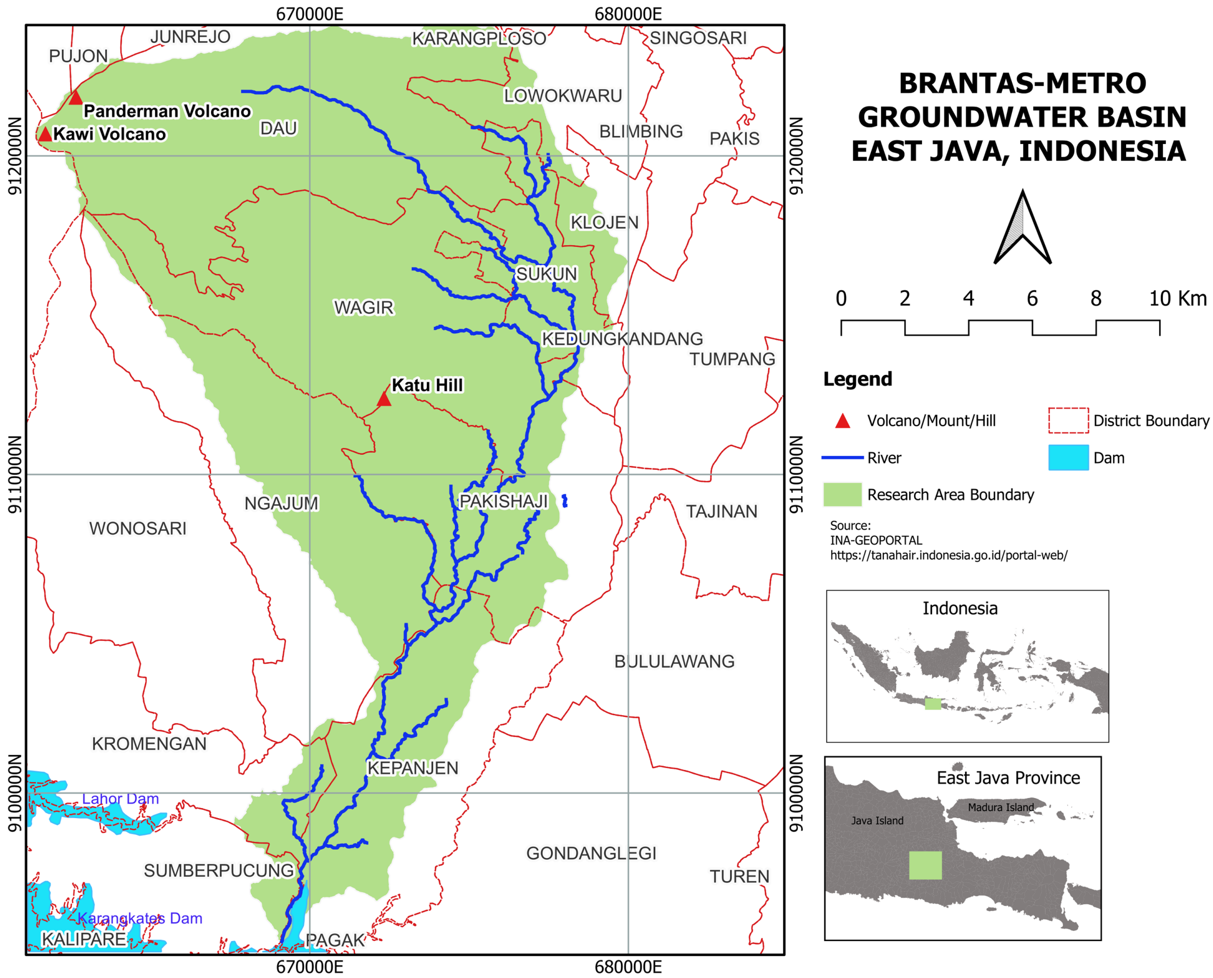

FIGURE 1
Research area.

regional regulation also states that the research location falls into several spatial categories, including: National Settlement Center with Malang City as its hub, Areas Providing Protection to Other Areas in the Form of Protected Forests (in the upstream of Kawi Volcano), Industrial Areas, Water Catchment Areas (Upstream Kawi Volcano), and Cultivation Areas (including Production Forests, Community Plantation Forests, Agricultural Areas, and Settlement Areas). Based on this regulation, there is a potential for a decrease in the extent of protected areas and water catchment areas, as well as an increase in community water demand. The further impact is the disruption of groundwater availability, especially shallow groundwater, as is the current condition. This situation is further exacerbated by regulations set by local governments that mostly concern the protection of areas around springs and deep groundwater aquifers. Local government regulations, such as Malang Regent Regulation No. 8 of 2015 concerning Sustainable Water Catchment and Infiltration Management, only discuss: water catchment area conservation, land-use control, flood prevention, construction of infiltration wells, and biopores. Regulations by the Central Government of the Republic of Indonesia also focus more on deep groundwater aquifers and do not consider shallow groundwater. However, there are quite a number of shallow groundwater users, especially in the research area (Figure 6).

The groundwater problems faced by the community in the research area are crucial and threaten groundwater sustainability. Groundwater sustainability can only be achieved through groundwater conservation. Groundwater conservation is essential to sustainability, but it is not fully adopted in the community (Kustamar et al., 2010). To fill this gap, this study used socio-hydrogeological approach to investigate community perspectives on groundwater management in the Brantas-Metro Groundwater Basin, Malang Region, Indonesia. Considering that each region has its own set of socio-hydrogeological characteristics, this research will provide new insights into the integration of social factors with hydrogeological science for this context. Also, since socio-hydrogeological studies for this study area are still in their infancy, this project will generate knowledge for future groundwater management strategies.

2.2 Research instrument

The research instrument is prepared based on the results of field observation and literature review. Previous research has shown that social factors, such as the role of the government (Carrión-Mero et al., 2021), community involvement, stakeholders, and socioeconomic

FIGURE 2
Unproductive wells in Ngajum village. Dug wells with brick walls, approximately 8 meters deep. The water in the wells is very minimal, rendering them unusable by residents. Water can only be collected using a bucket and rope.

factors (Hynds et al., 2018b), have previously been used to explain hydrogeology phenomena. However, previous studies indicate that socio-hydrogeology does not explicitly use Socio-Hydrogeological approach (Eléa et al., 2021; Frommen and Moss, 2021; Re et al., 2021a). Unlike earlier studies, this research employs three variables, each consisting of multiple sub-variables as detailed in Table 1. Each variable represents the Socio-Hydrogeological aspects defined by Re (2015). The use of variables and keys will clarify the community's comprehension of groundwater management in the study area.

This study used a questionnaire as its research instrument. A structured questionnaire was administered to survey respondents, incorporating key socio-hydrogeological considerations outlined (Re, 2015). Prior to data collection, the questionnaire underwent rigorous validity and reliability testing to ensure its validity and accuracy in measuring the intended constructs (Sugiyono, 2024). The Pearson product–moment correlation is employed to assess the validity of the instrument by examining the correlation between the score of each question item and the total score (Equation 1). In Equation 1, r_{xy} is the Pearson correlation coefficient between the variables x and y, while n is the sum of the sample or data pairs. Based on the number of respondents and the level of significance, the item is considered valid if the *r*-value of the analysis of the calculation results is higher than the *r*-value of the table derived from the statistical table. A comparison of the significance level and *p*-value can also be used for validation. The correlation is deemed significant, and the item is acceptable if the *p*-value (significance value) is less than the significance level (α, typically 0.05) (Sugiyono, 2024).

$$r_{xy} = \frac{n\left(\sum xy\right)-\left(\sum x\right)\left(\sum y\right)}{\sqrt{\left[n\left(\sum x^2\right)-\left(\sum x\right)^2\right]\left[n\left(\sum y^2\right)-\left(\sum y\right)^2\right]}} \quad (1)$$

The reliability of the questionnaire was tested using Alpha Cronbach. In Equation 2, the value α is the Cronbach's Alpha coefficient, the value N is the number of items, $\overline{c}$ is the average covariance value within the items, while $\overline{v}$ is the average variance value. The researcher utilized SPSS Statistics v27 to calculate the Cronbach's Alpha value. A high degree of internal consistency among the questionnaire items, indicated by a strong correlation between items relative to their individual variances, is crucial for reliability. Cronbach's Alpha ranges from 0 to 1, with values greater than 0.6 generally considered to indicate acceptable reliability (Taber, 2018).

$$\alpha = \frac{N\overline{c}}{\overline{v}+\left(N-1\right)\overline{c}} \quad (2)$$

2.3 Data acquisition and analysis

Population data for the study was sourced from the Central Statistics Agency of East Java Province (BPS Malang City, 2022; BPS Malang Regency, 2022). A sample of 100 respondents was selected using Proportional Stratified Random Sampling (Sugiyono, 2024). Respondents were chosen based on the following inclusion criteria: (1) residence within the research area; (2) a minimum educational attainment of a high school diploma; and (3) representation from each sub-district within the study area. The high school education requirement was implemented to ensure respondents could readily comprehend the questionnaire and because they are more likely to hold decision-making authority within their households.

The survey data were analyzed using descriptive statistics and Principal Component Analysis (PCA). PCA, a versatile statistical technique, is employed for various purposes, including factor analysis, correlation analysis, clustering, and classification. Its strength lies in simplifying data interpretation by Rahimi-Feyzabad et al. (2022), reducing dimensionality (Wang and Zhang, 2017) and mitigating noise by eliminating less informative components (Berenschot and Grift, 2019). As explained by Chowdhury et al. (2020), PCA optimizes the input vector dimensions while minimizing reconstruction error. The method yields eigenvalues, representing the variance explained by each principal component, with higher eigenvalues indicating greater variance. Factor loadings, also generated by PCA, reveal the contribution of each variable to a given principal component; high loadings signify a substantial contribution (Wang and Zhang, 2017; Chowdhury et al., 2020). The software used in analyzing PCA is SPSS Statistics v27. The device has the ability to analyze PCA quickly and comprehensively.

3 Results and discussion

3.1 General characteristics of respondents

A questionnaire was used to collect data for this study. Ensuring the reliability of this instrument is crucial for generating trustworthy

FIGURE 3
Cokro waterspring storage facility. Residents constructed an underground reservoir (tandon) to store groundwater. This facility is built beneath the ground on the slopes of Jedong Village Valley. Being located near the riverbank, it can collect a larger volume of water. The water is then pumped and distributed to residents' homes situated on higher slopes.

FIGURE 4
No water flow at Cokro spring. Cokro spring no longer flows into the river because the groundwater has been collected and stored in the storage facility.

data. Pearson's product moment validity testing revealed that all values were less than 0.05 (at a significant level of 0.05). Consequently, the instrument was declared valid. A Cronbach's alpha value of 0.871 was obtained, indicating strong internal consistency and thus good reliability. This level of reliability suggests the instrument could be suitable for similar research projects.

The respondents' primary occupations included civil servants (42, or 42.7%), such as village heads, government office staff, and village support staff; private sector employees (30, or 30.3%), working in fields like digital marketing, architecture, food sales, and small and medium-sized businesses; and other professions (28, or 27.0%), including students, housewives, teachers, and farmers. Regarding education, 42 respondents (41.6%) held university degrees, while 58 (58.4%) had completed high school (both general and vocational). Most respondents (69, or 68.5%) resided in residential areas, with the remainder living near business and industrial development areas, dan agricultural area. Of the respondents, 60 (60%) used groundwater as a water source, while 40 (40%) relied on government-operated piped water networks. The groundwater users obtained water from a variety of sources, including community-owned piped networks (fed by

FIGURE 5
Dry irrigation channels. Irrigation flows from Sawah Valley Watersprings toward the agricultural lands of Wagir District.

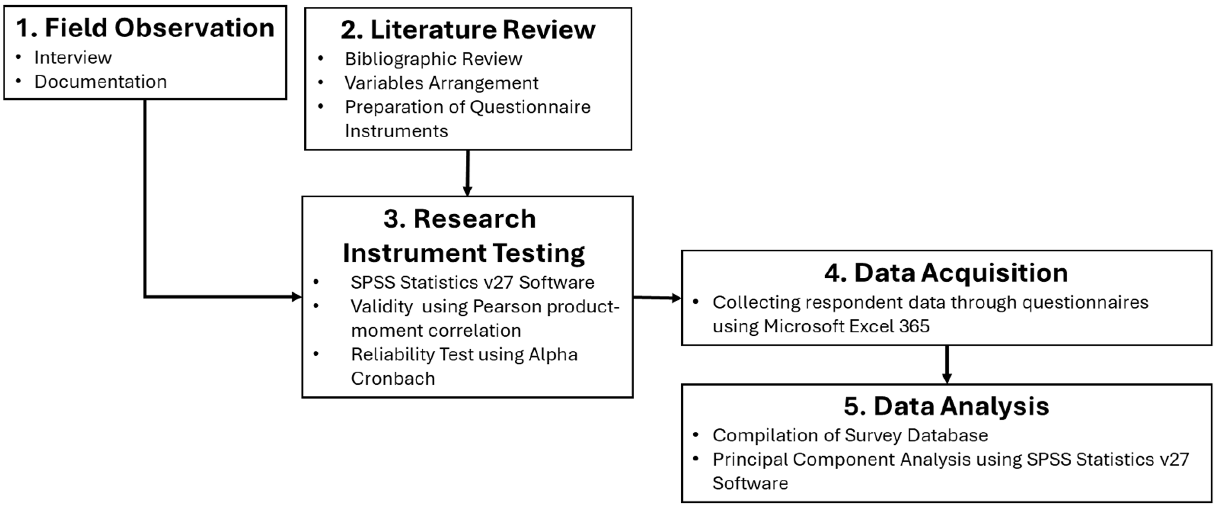

FIGURE 6
Research workflow.

springs), shallow drilled wells, shallow dug wells, and direct access to springs. Respondents who obtain water from government-operated piped water networks are classified as non-groundwater users.

3.2 Community awareness

Awareness can be defined as a human attitude or behavior formed as a result of certain consequences that lead to a positive attitude. One way to determine an individual's level of awareness is through the cognitive component. The cognitive component is expressed as the knowledge an individual possesses about a specific situation (Ham Josip Juraj Strossmayer et al., 2015). Consequently, community awareness relates to collective human attitudes or behaviors. Prior research has demonstrated a link between insufficient community awareness and groundwater challenges, such as over-extraction and the risk of seawater intrusion, as public conditions in Baton Rouge, Louisiana (Hemmerling et al., 2024). Research in the Republic of Ireland shows that the enhancement of community awareness at both regional and local levels is the most effective strategy for groundwater

TABLE 1 Research variables based on the socio-hydrogeology approach.

No	Variables	Sub variables	ID	Indicators
1	Community awareness	Groundwater management knowledge	STP1	Well Condition
2			STP2	Determine Impact Method
3			STE1	Over-pumping Impact
4			STE3	Evaluation of Over-pumping Impact
5		Community awareness efforts	STI1	Stakeholders Identification
6			STI3	Issues and conflict risks
7			SSP1	The significance of groundwater management
8			SSP2	Promotion of hydrogeological research
9			SSM1	Periodic Discussion
10			SSM3	Groundwater information distribution
11			SSI1	Educational Programs
12	Community participation	Types of community involvement	TMP2	The extent of the community involved
13			TMP3	Community Involvement in Impact Assessment
14			TME2	Assessment of Community Activity Types
15			TME3	Assessment of Over-pumping Effects
16		Management program implementation	TJI1	Program Identification
17			TJI2	Identify targets, program outcomes, and conflict risks
18			TSP3	Willingness to Participate in the Program
19		Willingness to exchange data and information	TSM1	Fully involved in the socialization of the Groundwater Management Program
20			TSM3	Willingness to participate as a participant in the groundwater conservation program
21			TSI1	Publication of hydrogeological investigation results
22			TSI3	Hydrogeology experts' involvement
23	The ability to accept and adapt to information, technology, and disaster risks	The ability to accept information, technology, and disaster risks	MMD1	Independent information-seeking
24			MMD2	Receiving and understanding the impact of information of activities
25			MME1	Saving/conserving independently under conditions
26			MME3	Understanding the societal consequences of inaccurate information
27			MMI1	Recognition of management ineffectiveness
28			MMI3	Ability to resolve organizational conflicts
29		The ability to adapt to changes in groundwater conditions	MMP2	Capable of adjusting and responding upon obtaining information
30			MMP3	Use innovative technology to solve groundwater problems
31			MMJ2	Requesting government, academic, and NGO support
32			MMJ3	Capacity to adjust to new technology
33			MMU1	Access to hydrogeological data
34			MMU3	Developing new technology in hydrogeology

management (Mooney et al., 2020). Community awareness is crucial for effective groundwater management. Increased awareness empowers communities to actively participate in such efforts.

Figure 7 presents respondent opinions regarding Community Awareness, a variable comprised of two sub-variables and 11 parameters (Table 1). Responses are categorized for all respondents, groundwater users, and non-groundwater users. Regarding the significance of groundwater management (SSP1), 32.6% of respondents strongly agreed. A larger proportion (76.4%) agreed with the importance of periodic discussions related to groundwater management (SSM1). However, a notable minority (28.1% combined) expressed disagreement (18%) or strong disagreement (10.1%) with the indicator related to knowledge of groundwater well conditions (STP1), within the sub-variable concerning knowledge of groundwater management.

Respondents were categorized as groundwater users and non-users. Both groups showed similar levels of strong agreement (33%) regarding the importance of groundwater management (SSP1). Among groundwater users, 76% agreed with the need for periodic discussions to raise community awareness (SSM1). Non-groundwater

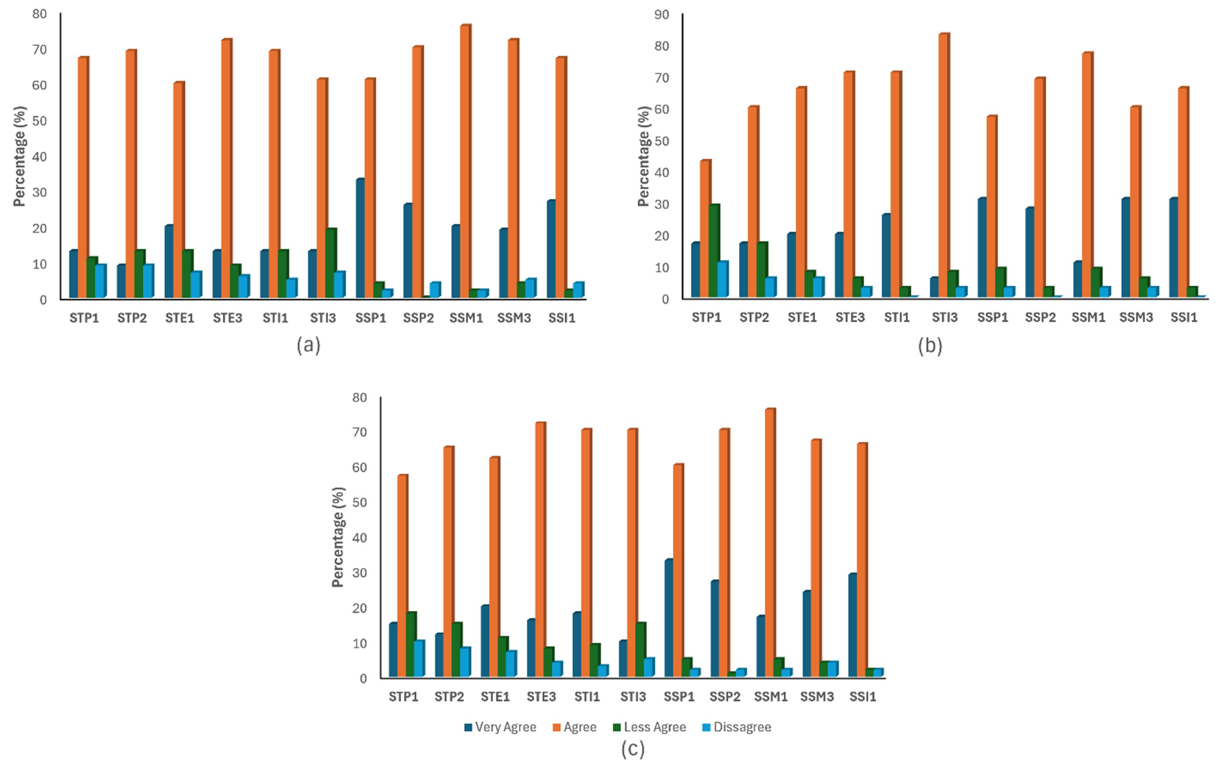

FIGURE 7
Respondents' perception of community awareness on the socio-hydrogeology approach. **(a)** Groundwater users, **(b)** Non-groundwater users, and **(c)** Overall respondents.

users frequently agreed (83%) with the importance of community awareness efforts regarding issues and conflict risks (STI3). Notably, groundwater users differed from non-users in their perception of conflict risks, with groundwater users less likely to consider excessive groundwater use as a significant conflict risk. This aligns with prior study indicating that groundwater extraction by well owners will not result in issues with groundwater, hence they will continue in extracting water (Bostic et al., 2023).

Increased community awareness is essential for understanding the environmental challenges associated with groundwater. Studies have shown that limited awareness can lead to future complications, as observed in Myanmar (Re et al., 2021b) and Vietnam, where a lack of groundwater management has contributed to numerous problems (Pham et al., 2023). Enhanced education is a key strategy for improving public understanding of groundwater management (Mooney et al., 2021). This aligns with broader research indicating a positive correlation between education levels and community awareness of groundwater management (Ahmed et al., 2021; Re et al., 2021b). While this study confirms the importance of community awareness, it further distinguishes between groundwater users and non-users, particularly in their perceptions of conflict risk. Potential conflict triggers include water quality changes, decreased supply, and excessive extraction.

3.3 Community participation

Arnstein (1969) explained that participation constitutes a mechanism of power sharing, enabling citizens lacking authority to engage intentionally and actively in the decision-making process. Citizens have several conditions of participation, including non-participation (not involved in decision-making), Degrees of Tokenism (superficial), and Degrees of Citizen Power (active) (Arnstein, 1969). The public's participation in water resources management is dependent upon their own factors, according to research conducted in the United Kingdom (Fritsch, 2017). Government policies, family, socioeconomic level, and possible risks are some of the factors that influence whether or not someone chooses to participate (Fritsch, 2017; Kabogo et al., 2017; Ocampo-Melgar et al., 2022; Xiaomei, 2023). Research indicates that community participation is very important and the most effective element in integrated water resources management (Ali and Kamraju, 2024). Participation may escalate when issues emerge that have extensive impacts (Barthel et al., 2017). Previous studies indicated that the participation of groundwater users surpasses that of non-users (Mooney et al., 2020). Thus, community participation can be defined as the involvement of communities without authority in the decision-making process.

Regarding community involvement (TME2), 24% of respondents (both users and non-users) strongly agreed with the need to evaluate community activity types (Figure 8). A larger proportion (71%) agreed with this evaluation (TME2) and also with the importance of identifying aims, program outcomes, and potential conflict risks within groundwater management programs (TJI2). This indicates general agreement on the value of evaluating program participation and understanding program goals, outcomes, and potential conflicts. However, a substantial minority (26%) disagreed with the need for hydrogeology expert involvement and willingness to participate in groundwater management programs (TSI3 and TSP3, respectively). This discrepancy suggests that while respondents recognize the importance of program evaluation and identification of key program elements, they are less inclined toward expert involvement and direct program participation. This finding echoes research in Maneadero Valley, Mexico, which suggests that community participation is not always sustainable, potentially due to factors like diminishing power and ineffective participation mechanisms (Villada-Canela et al., 2021).

Groundwater users most strongly agreed (22%) with the need to assess the effects of overpumping (TME2). A similar level of strong agreement was observed regarding the identification of targets, program outcomes, and conflict risks within groundwater management programs (TJI2). However, respondents expressed disagreement or strong disagreement with the involvement of hydrogeology experts (TSI3). Non-groundwater users, in contrast, strongly agreed with the need to assess community activity types (TME2) and the publication of hydrogeological investigation results (TSI1). Among groundwater users, 71% agreed with the assessment of over-pumping effects (TME3). Disagreement or strong disagreement was again noted regarding hydrogeology expert involvement and willingness to participate in management programs (TSI1 and TSP3, respectively). These findings suggest a general willingness among both user and non-user groups to evaluate management impacts and identify key program elements. In TSP3, 25% of all respondents stated they strongly disagreed with participating in the groundwater management program. In fact, 20% of groundwater users and 31% of non-groundwater users stated they strongly disagreed with participating. According to Arnstein's degree of participation, they are classified as non-participating citizens (1969). Only 9% of groundwater users and non-groundwater users are willing to actively or fully participate (TSM1). This indicates that the willingness for full participation in groundwater management is still relatively low. This reluctance may stem from social, economic, cultural, and knowledge-based factors that influence participation (Bernacchi et al., 2020). Therefore, collaborative efforts among all stakeholders are crucial to foster genuine community participation. Developing participatory scenarios that promote mutual understanding is one such strategy (Rouillard et al., 2022). Kengganan berpartisipasi ini mirip dengan penelitian sebelumnya di (Hund et al., 2018; Oshun et al., 2021; Khadim et al., 2023).

3.4 The ability to accept and adapt to information, technology, and disaster risk

The variable concerning the Ability to Accept and Adapt to Information, Technology, and Disaster Risks is crucial for understanding individual capacity in groundwater management. This capacity is essential for navigating various potential environmental changes, including those impacting groundwater (Lal et al., 2018). Understanding this adaptive capacity can inform the development of more effective management approaches, particularly given the current landscape of readily available information, diverse technologies, and increasing disaster risks (Hendrickson and Bruguera, 2018). Information access, often through media channels, can significantly

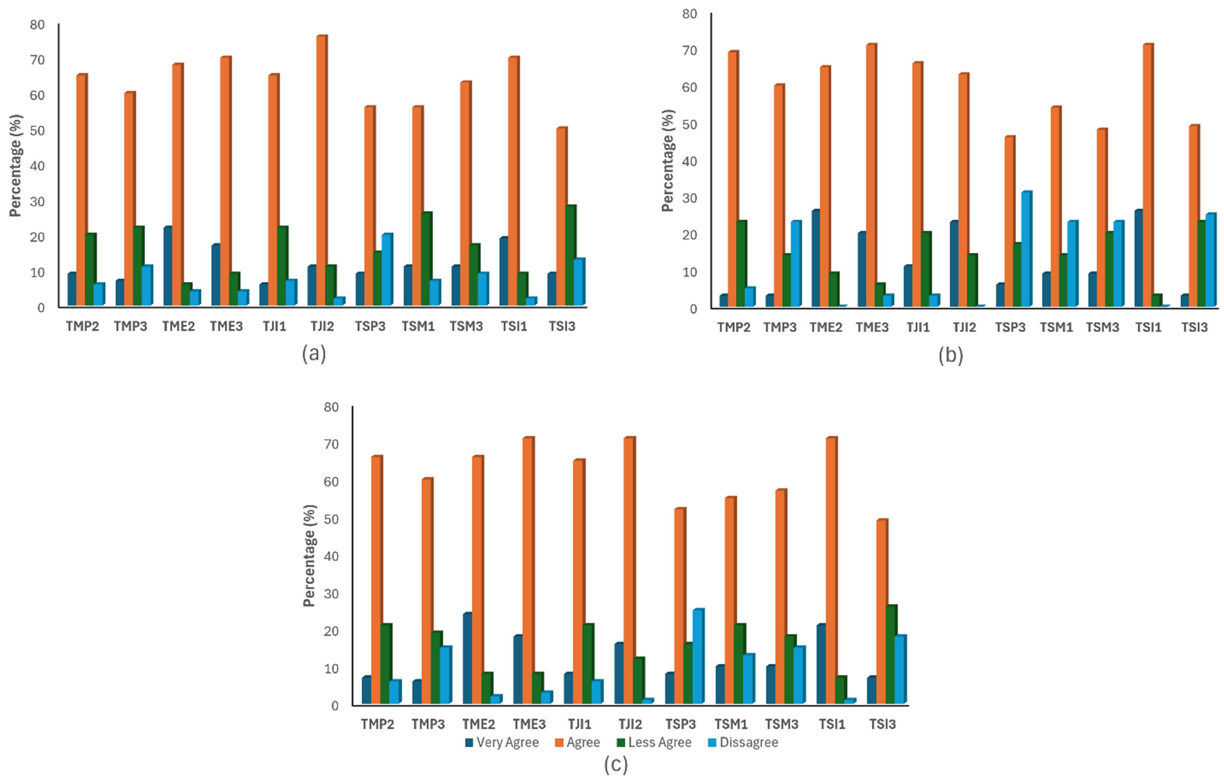

FIGURE 8
Respondents' perception of community participation on the socio-hydrogeology approach. **(a)** Groundwater users, **(b)** Non-groundwater users, and **(c)** Overall respondents.

shape community perceptions and concerns (Bernacchi et al., 2020). Informed adaptation strategies enhance community resilience to environmental changes and mitigate stress on both individuals and their environment (Elpida and Dimitrios, 2020). Effective adaptation requires comprehensive strategies involving all community stakeholders (Aida et al., 2020).

Overall, respondents strongly agreed with the "Saving/Conserving Independently Under Conditions" indicator within the "Ability to Accept and Adapt to Information, Technology, and Disaster Risks" sub-variable (MME1) (Figure 9). Regarding adaptation to changing shallow groundwater conditions (MMJ2), respondents more frequently agreed with the need for support from the government, academia, and NGOs. However, disagreement was noted concerning the "Recognition of management ineffectiveness" indicator and the "Ability to resolve organizational conflicts" indicator (MMI3). Furthermore, respondents disagreed with the "Independent information-seeking" indicator within the "Ability to accept information, technology, and disaster risks" sub-variable (MMD1).

Respondents were categorized as groundwater users and non-users. Among groundwater users, 15% strongly agreed with the "Saving/conserving independently under conditions" indicator within the "Ability to accept information, technology, and disaster risks" sub-variable (MME1), and another 15% strongly agreed with the "Developing new technology in hydrogeology" indicator within the "Ability to adapt to changes in groundwater conditions" sub-variable (MMU3). A larger proportion of groundwater users (81%) agreed with the "Saving/conserving independently under conditions" indicator (MME1). However, 26% of groundwater users disagreed with both the "Recognition of management ineffectiveness" indicator within MMI1 and the "Ability to resolve organizational conflicts" indicator within MMI3. This pattern suggests that while groundwater users are receptive to new technologies and information related to water conservation, they are less likely to support organizations they perceive as ineffective in implementing groundwater management initiatives or resolving related issues. Non-users, unlike groundwater users who prioritized independent action (MME1), more readily agreed with the need to adapt to changing groundwater conditions by seeking assistance from government, scientist/academic, and NGO entities (MMJ2 and MMJ3). In essence, groundwater users demonstrate a preference for independent conservation efforts, whereas non-users are more inclined to rely on external support.

3.5 Socio-hydrogeology factor analysis

Principal Component Analysis (PCA) was used to identify the primary factors among the research variables. Communalities in PCA represent the proportion of each variable's variance explained by the principal components (Li et al., 2023). The highest communality (0.883) was observed for the "Willingness to Participate in the Program" indicator within the "Management Program Implementation" sub-variable (TSP3). While respondents generally supported the existence of groundwater management programs, a disconnect emerged regarding participation. Many respondents, despite their support for the programs, did not perceive a need to be actively involved. Consequently, the lack of community participation

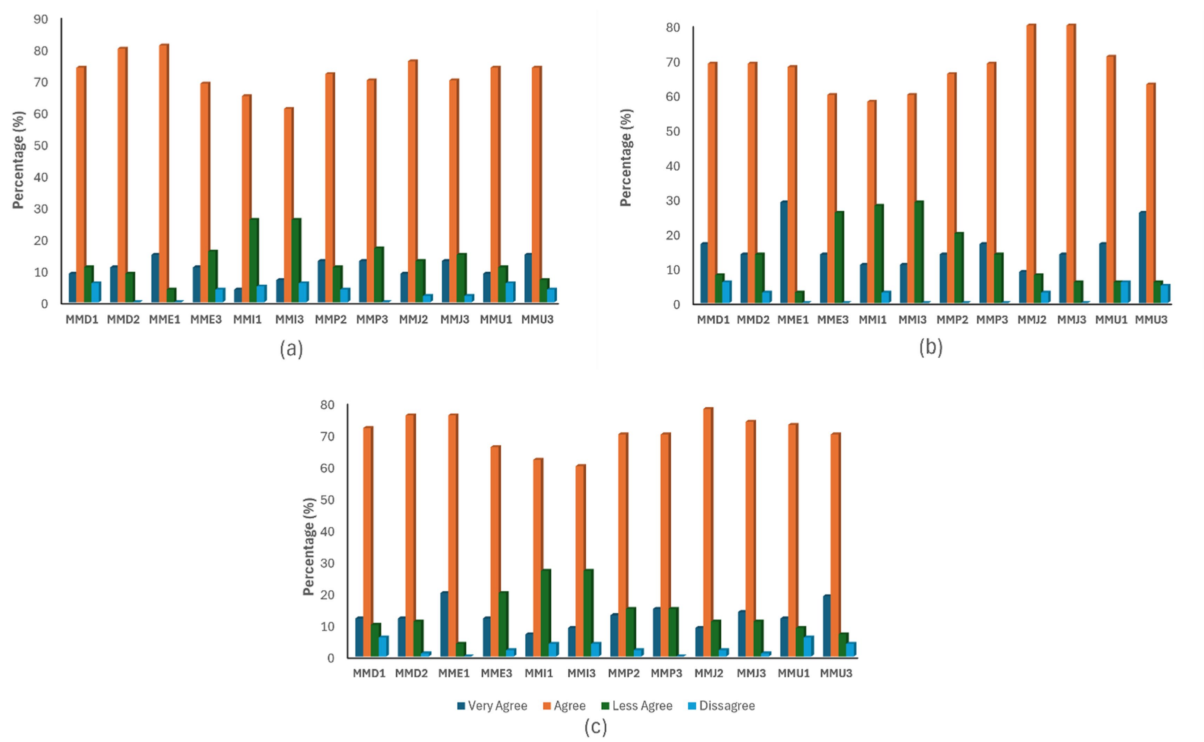

FIGURE 9
Respondents' perception of ability to accept and adapt to information, technology, and disaster risk on the socio-hydrogeology approach. **(a)** Groundwater users, **(b)** Non-groundwater users, and **(c)** Overall respondents.

may lead to sustainability challenges in groundwater management (Mooney et al., 2021). A separate study indicates that if the community is unwilling to participate, alternative options are necessary for groundwater management. The local government, as the primary administrator, can designate the communities under its authority as groundwater managers (Baran et al., 2021).

The second highest communality (0.876) was observed for the "Recognition of management ineffectiveness" indicator within the "Ability to Accept and Adapt to Information, Technology, and Disaster Risks" variable (MMI1). Most respondents disagreed with this indicator, asserting that groundwater management is not ineffective and that conflicts among stakeholders are minimal. While academic literature suggests that groundwater conflicts typically arise from diminishing water availability, declining water tables, water quality changes, and limited access to wells (Jia et al., 2019; Santos et al., 2019; Sen et al., 2020) and can even escalate to communal violence (Döring, 2020). Respondents in this study area did not perceive these conditions as problematic or conflict-inducing. This discrepancy highlights a difference in problem definition between academic theory and local experience. When faced with groundwater issues, respondents generally preferred to seek independent solutions, often consulting local experts such as well diggers. Involvement of external parties like government agencies, academics, hydrogeologists, and NGOs was typically reserved for situations beyond the community's capacity to resolve independently (Nazari and Ahmadi, 2019; Döring, 2020). Consequently, overt conflicts related to groundwater were rare and largely unacknowledged within the community (Table 2).

The third highest communality (0.841) was associated with the "Over-pumping Impact" indicator within the "Groundwater Management Knowledge" sub-variable of the Community Awareness variable (STE1). Responses regarding the effects of excessive groundwater extraction varied considerably, indicating diverse perspectives on this issue. Declining groundwater levels in the area are a consequence of overpumping, driven by increased community demand (Mukherjee et al., 2018; Jain et al., 2021). This demand is likely to escalate with continued population growth and economic development across sectors like industry, agriculture, residential use, and drinking water consumption (Yin et al., 2017; Bierkens and Wada, 2019; Elshall et al., 2020). Existing research confirms the link between overpumping and groundwater depletion (Somaratne et al., 2013; Koïta et al., 2018; Jena et al., 2020). In this study, most respondents, both users and non-users, acknowledged the social consequences of excessive groundwater extraction and recognized the potential need to seek alternative water sources as a result of groundwater changes.

The lowest communality (0.552) was observed for the "Significance of groundwater management" indicator within the "Community Awareness Efforts" sub-variable (SSP1). Low communality values suggest that this indicator may not be strongly related to the other variables in the analysis and may not contribute significantly to the overall model (Li et al., 2023). Despite this, respondents generally agreed or strongly agreed with the importance of groundwater management. Effective groundwater management is indeed crucial for the long-term sustainability of this vital resource (Kabogo et al., 2017; Rahimi-Feyzabad et al., 2022).

Principal Component Analysis (PCA) revealed 10 components. Table 3 shows the eigenvalue of these 10 components. Overall, these 10 components collectively explain 74.605% of the total variance in the data. Based on Kaiser's criterion (eigenvalue > 1), all 10 components qualify for retention. The first component exhibits the highest eigenvalue (8.591), indicating substantial variability within the data. This first principal component accounts for 25.269% of the total data variance and is crucial for identifying primary data patterns. The eigenvalue table is used to generate a scree plot, which is its graphical illustration (Figure 10). From the scree plot results, four main components were identified: 1, 2, and 3. These components contribute significantly to the overall variance, a characteristic often associated with eigenvalues exceeding 1 (Li et al., 2023).

The scree plot from the PCA analysis results show three main components (Figure 11). The curve's decline slows down after Component 3, characterized by an elbow point. This indicates that components after this point have significantly less variance and may be less informative. Figure 11 also depicts the component plot. The component plot has three axes: X, Y, and Z. The X-axis represents Component 1, which accounts for the biggest variability. The Y-axis represents Component 2, derived from the remaining variability values that are uncorrelated with Component 1. The Z-axis represents Component 3, which provides additional information from the preceding components. The component plot can help identify sub-variables that tend to cluster together. Sub-variable clusters that exhibit similar variations will appear in close proximity. The component plot in this study yielded two clusters. Cluster 1 (yellow circle) shows positive values on Components 1 and 3, but negative values on Component 2. Cluster 1 includes the sub-variables STP2, STE1, STE3, STI1, STI3, SSP1, SSP2, SSM1, SSM3, TMP2, TME2, TME3, and TJI1. Cluster 1 is dominated by the variables 'Community Awareness' and 'Community Participation'. Cluster 2 (red circle) shows positive values on Components 1, 2, and 3. Cluster 2 includes the sub-variables: STP1, TMP3, TSP3, TSM1, TSM3, TSI1, TSI3, MMD1, MMD2, MME1, MME3, MMI1, MMI3, MMP2, MMP3, MMJ2, MMJ3, MMU1, and MMU3. This cluster is dominated by 'The Ability to Accept and Adapt to Information, Technology, and Disaster Risks'. Although the component plot can assist in interpreting patterns within the research sub-variables, it is not yet able to fully display the names of all sub-variables, such as SSM3, TJI2, TSI1, and TSI3.

The Component Matrix resulting from the PCA includes 10 components and their corresponding loadings. Higher loading values (approaching 1 or −1) indicate a stronger contribution of the variable to the principal component. While the first component represents the overall situation, subsequent components capture more specific variations. The variable with the highest loading on the first component is considered the dominant factor. In this case, the highest loading value (0.687) was observed for the "Groundwater information distribution" indicator within the "Community awareness efforts" sub-variable of the Community Awareness variable (SSM3). This high, positive loading signifies the variable's substantial influence and positive correlation with socio-hydrogeology. In this study, a higher loading value suggests that effective groundwater information distribution can significantly enhance community awareness, a crucial factor for successful groundwater management (Kabogo et al., 2017; Medrano-Pérez et al., 2022). This also suggests that respondents recognize the importance of groundwater information distribution for raising public awareness. Such programs, potentially delivered in collaboration with external experts, can foster new relationships among stakeholders, facilitating knowledge exchange and open dialogue. Information distribution can also be carried out through mass media, website development, and mobile apps (Hynds et al.,

TABLE 2 Respondent profile in the research area.

No	Respondent profiles		Total	Percentage (%)
A	Occupation			
	1	Teacher	4	4
	2	Housewife	9	9
	3	Civil Servants	42	42
	4	Student	12	12
	5	Farmer	3	3
	6	Private Sector	30	30
B	Educational background			
	1	University	42	42
	2	General High School	38	38
	3	Vocational High School	20	20
C	Water source			
	1	Government-owned water pipe networks	40	40
	2	Community-owned water pipe networks	16	16
	3	Springs	10	10
	4	Shallow Drilled Well	10	10
	5	Shallow Dug Wells	24	24
D	Land use			
	1	Residential	69	69
	2	Business and Industrial Development Area	3	3
	3	Agricultural Area	28	28
E	Water usage			
	1	Washing, bathing, cooking	82	82.02
	2	Washing, bathing, cooking, Others	1	1.12
	3	Washing, bathing, cooking, farming	1	1.12
	4	Washing, bathing, cooking, farming, service business	4	4.49
	5	Washing, bathing, cooking, farming, service businesses, medium-sized companies	1	1.12
	6	Washing, bathing, cooking, medium-sized companies	4	3.37
	7	Washing, bathing, cooking, medium-sized companies, Others	1	1.12
	8	Washing, bathing, cooking, service business (e.g.: cakes, laundry, motorbike/car washing)	1	1.12
	9	Farming	1	1.12
	10	Other	4	3.37

2018b), making it easily accessible to a wider community. Ultimately, the goal of these programs is to empower the community to effectively manage groundwater resources (Rouillard et al., 2022).

The variable with the highest negative loading (−0.508) was the “Overpumping Impact” indicator within the “Groundwater Management Knowledge” sub-variable of the Community Awareness variable (STE1). This suggests that while respondents acknowledge the existence of overpumping impacts, their understanding of the underlying processes may be limited. Although this indicator had the third-highest communality, indicating its importance, it received less direct attention from respondents. Overpumping, a significant anthropogenic activity, is often overlooked, despite its potential for irreversible environmental damage (Ashraf et al., 2021). Such consequences include land subsidence and drought, both of which can be exacerbated by climate change (Haacker et al., 2019; Iquebal et al., 2021; Bremard, 2022; Chen et al., 2023).

The PCA correlation matrix revealed a strong positive correlation (0.784) between respondents' willingness to participate in groundwater management programs (TSP3) and their views on the involvement of hydrogeology experts (TSI3). This suggests that a greater willingness to participate is associated with a stronger belief in the value of expert involvement. This finding supports the core principle of socio-hydrogeology, which emphasizes knowledge transfer to the community, and is consistent with prior research demonstrating the importance of integrating social considerations with hydrogeological expertise for effective groundwater management (Limaye, 2017; Re et al., 2021b).

Figure 12 depicts the key socio-hydrogeological elements identified in the study area, which should be considered in local groundwater management strategies. Notably, the assessment of the social implications of groundwater resource changes (quality and quantity) on human well-being was not identified as a significant factor by respondents, who generally did not perceive such changes as having social consequences, thus diminishing the perceived need for formal evaluation. While respondents demonstrated a good understanding of hydrogeological conditions and groundwater management approach, including the impacts of over-extraction, they exhibited a reluctance to participate in management initiatives. This reluctance aligns with their perception of ineffective groundwater management. However, these discrepancies between perceived problems and willingness to act should be addressed by stakeholders, as they can lead to future challenges (Karjalainen et al., 2013; Rahimi-Feyzabad et al., 2022; Bernat et al., 2023). Respondents did, however, support improved groundwater information dissemination and the involvement of hydrogeology experts, which could potentially increase community participation (Re et al., 2018). Critically, Groundwater Information dissemination emerged as a key factor for enhancing both community awareness of groundwater conditions and participation in management efforts. Overall, a socio-hydrogeological approach, by incorporating community

TABLE 3 Eigenvalue in each research component.

Component	Eigenvalues		
	Total	% of Variance	Cumulative %
1	8.591	25.269	25.269
2	4.166	12.254	37.522
3	2.64	7.763	45.286
4	2.146	6.313	51.599
5	1.721	5.063	56.661
6	1.593	4.685	61.347
7	1.26	3.707	65.054
8	1.145	3.367	68.421
9	1.094	3.218	71.639
10	1.008	2.966	74.605

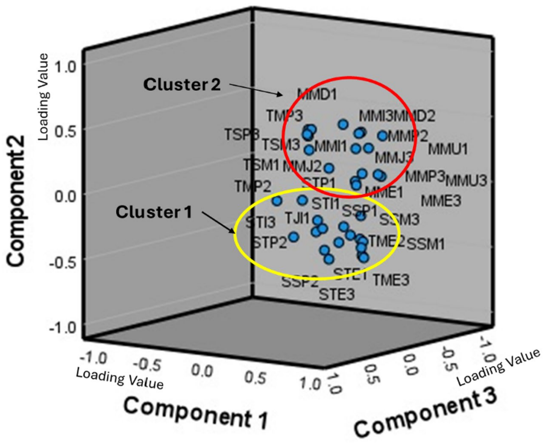

FIGURE 11
Component plot of PCA.

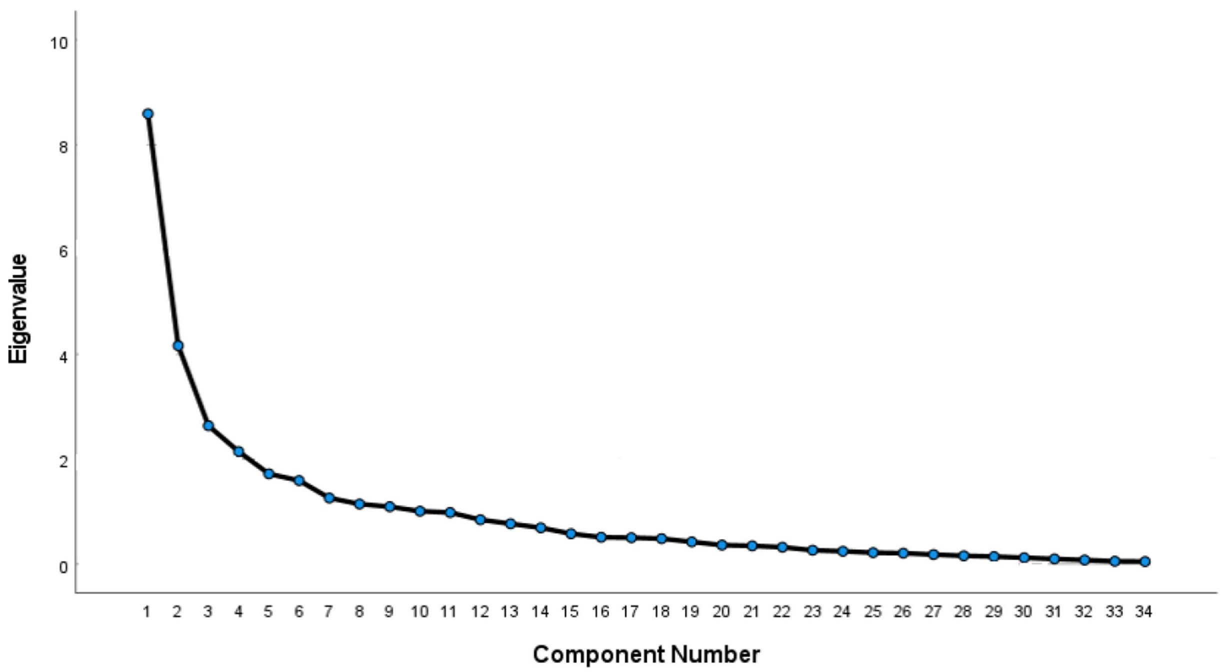

FIGURE 10
Scree plot of PCA.

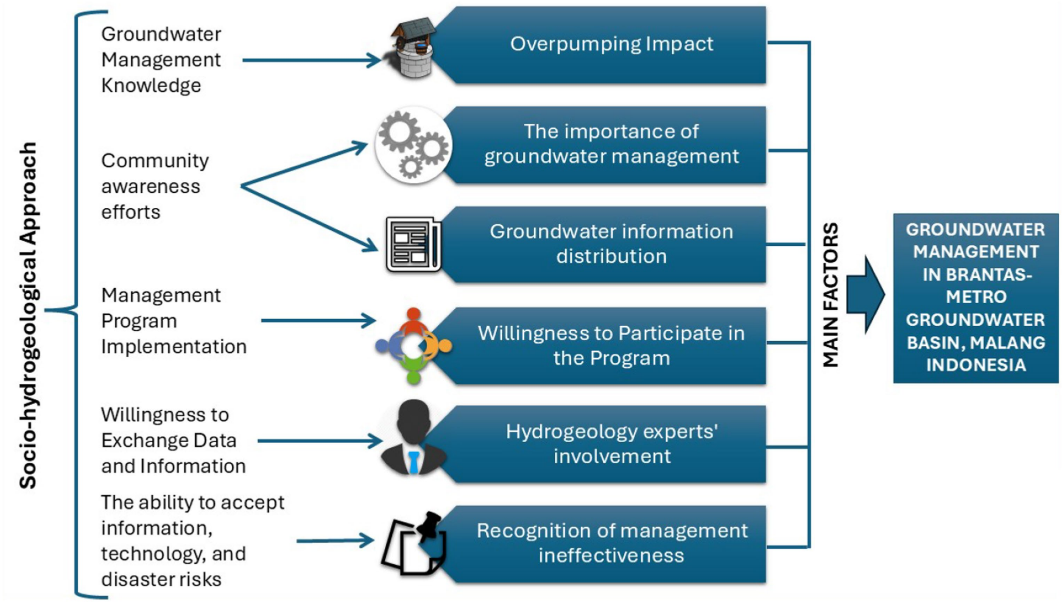

FIGURE 12
Construction of the main socio-hydrogeology factors in the Brantas-Metro Groundwater Basin, Malang.

perceptions, offers a promising pathway toward achieving groundwater sustainability in the study area.

This research has several limitations that may affect the generalization of its results. The data comes from a perception-based study without real groundwater monitoring therefore it reflects public opinion rather than physical conditions. The research also has a limited number of respondents and the specific coverage area in the Brantas-Metro Groundwater Basin may restrict the applicability of these results to other regions with different social and hydrogeological conditions. The analysis used (Principal Component Analysis) in this research is effective in identifying main factors but cannot directly show cause-and-effect relationships. Further studies with more extensive methods and a larger sample size are needed to strengthen these findings.

4 Conclusion

Socio-hydrogeology provides an interdisciplinary framework for linking groundwater issues with social processes, which is important since groundwater sustainability is inherently a social problem. Questionnaires were distributed based on predetermined criteria in this study to survey the management of groundwater in Brantas-Metro Groundwater Basin. Although the survey responses converge on agreement regarding the factors and sub-variables explored, Principal Component Analysis (PCA), revealed Willingness to Participate in the Program as a major driver. Other main socio-hydrogeological factors derived from PCA analysis include (1) Overpumping Impact, (2) The Importance of Groundwater management, (3) Groundwater Information Dissemination, (4) Hydrogeologist Involvement, and (5) Management Ineffectiveness recognition. The community members had a good general knowledge of groundwater management, yet they were hesitant to get involved in groundwater management initiatives. Hence, the key to community awareness and active involvement in groundwater management will be through the consultation of various other stakeholders including hydrogeology experts as well as government organizations. Through this participation, the community will increase their capacity to adapt and mitigate challenges associated with groundwater in their region. These discoveries provide important information for future research and groundwater management plans in the region.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical approval was not required for the studies involving humans as the studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required from the participants or the participants' legal guardians/next of kin in accordance with the national legislation and institutional requirements.

Author contributions

FM: Validation, Writing – review & editing, Formal analysis, Writing – original draft, Methodology, Conceptualization, Investigation. MB: Investigation, Writing – review & editing, Supervision, Writing – original draft, Validation, Methodology, Conceptualization. BS: Writing – review & editing, Writing – original draft, Methodology, Investigation. SW: Writing – review & editing, Resources, Writing – original draft, Formal analysis, Methodology.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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