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Why indigenous water systems are declining and how to revive them: A rough set analysis

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ABSTRACT

For many centuries, rainwater harvesting (RWH) was the main source of water in many ancient countries. However, over the last four decades, its use has been declining steadily. RWH structures fell into disrepair and were abandoned or were only occasionally used. Taking Sana'a Basin in Yemen as a case study, we examined the underlying factors for the decline and explored ways to reverse it. We interviewed 100 farmers and 65 experts and visited 22 RWH systems, both abandoned and still in use. We used rough set analysis to analyze RWH systems data. The overall results showed that the government plays a crucial role in the operational status of the RWH systems. However, the government's rhetoric on the importance of investing in traditional RWH, very few projects were actually implemented or maintained. In contrast, access to groundwater was heavily promoted making it the preferred water source. However, the water table became depleted and there was a dependency on diesel. Other socioeconomic factors including ownership, limited capacity of RWH systems, the availability of imported food, and rural-urban migration were other secondary reasons for abandonment. Without a shift in government support from groundwater to rainwater harvesting, this long-term decline is likely to continue.

1. Introduction

Archaeologists have long studied the indigenous techniques for accessing and managing water supplies, which played a vital role in the survival and social prosperity of ancient societies (Harrower 2010; Paz-Kagan et al., 2017). Water harvesting is an ancient technology that is practiced around the globe. Rainwater harvesting (RWH) systems were often the main source of water in ancient times, particularly in arid and semi-arid countries (Varisco, 2019). Indigenous RWH systems were made of local materials and were characterized by solution-oriented, minimum-intervention, maximum-effect designs (Vetter and Rieger, 2019a). Precipitation and land accessibility were important factors in determining the type of RWH system and the settlers' choices of crops and grazing activities (Harrower, 2010). Some of the most well-known of the traditional systems are the ancient Southwest Arabian irrigation technologies, which developed over thousands of years and culminated in some of the ancient world's most advanced flash-floodwater systems (Beckers et al., 2013; Harrower 2010; Harrower and Nathan, 2018).

The cutting-edge knowledge of RWH practices in arid areas has underscored the fact that they are more than ecosystems; they have also been home to generations of indigenous communities (Vetter and Rieger, 2019b). For instance, water scarcity has been a perpetual threat to livelihoods throughout Yemen's history (Hehmeyer, 2019). However, pre-modern Yemeni societies developed a variety of sustainable water management strategies (Ward and Unruh 2016) to the extent that by the mid-10th century, the country was known as "Verdant Yemen" (Varisco, 2019). These strategies were adapted to the specific regional rainfall patterns: in the highlands, agriculture was historically rain-fed, while foothills and coastal areas were traditionally irrigated by seasonal floods (Muharram and Alsharjabi, 2019). Moreover, these strategies were comprehensive, and incorporated engineering works as well as related political and legal arrangements. The sustainability of these traditional systems is demonstrated both by their adaptation to Yemen's difficult hydrology, and their durability throughout Yemen's pre-modern history (Almas and Scholz, 2006).

Indigenous RWH systems were judged by experts to be remarkably effective. Viziterv-Vituki (1971) concluded that "the existing system of water rights is logical and may be kept unchanged," while Varisco

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(1983) considered the Yemeni community-management system to be "the most efficient method for flood irrigation." However, after the 1960s, the sustainable engineering, political, and legal systems that had characterized indigenous Yemeni water management began to decline (Al-Wadaey and Bamatrf, 2010; Bamatraf, 1994; Beckers et al., 2013; Moore 2011), and a lack of data makes it difficult to determine the decisive factors behind this decline.

Although the importance of indigenous RWH systems and the positive impact of their revival have been highlighted in several studies (Aklan et al., 2019; Harrower and Nathan 2018, Vetterand Rieger, 2019b), it is essential to first understand why these systems are declining. Knowing why people abandoned these systems may help to understand what tools and incentives are needed to revive them. Thus, this study aims to assess the factors that have led to the increasing abandonment of traditional water-harvesting systems. To overcome the lack of data, the study used a field survey and a data mining method known as rough set analysis.

Two sub-basins within the Sana'a Basin in Yemen were selected as case study areas, with local farmers, academics, and water and agriculture selected to participate in this study as the main stakeholders. Artificial data mining methods along with in-depth interviews, stakeholder group meetings, site investigations, and measurements for selected systems were the main methods of study.

2. Materials and methods

2.1. Study area

Two sub-basins within the Sana'a Basin in Yemen, Wadi Zahr and Wadi Mulaikhy, were selected as the study areas. They are located on the upper west side of the Sana'a Basin and cover an area of 441 km^2 (Fig. 1). Rainfall in the two sub-basins ranges between 180 and 260 mm per year, the highest in the Sana'a Basin area. As they are located in the upstream mountain area, groundwater availability is lower than in the

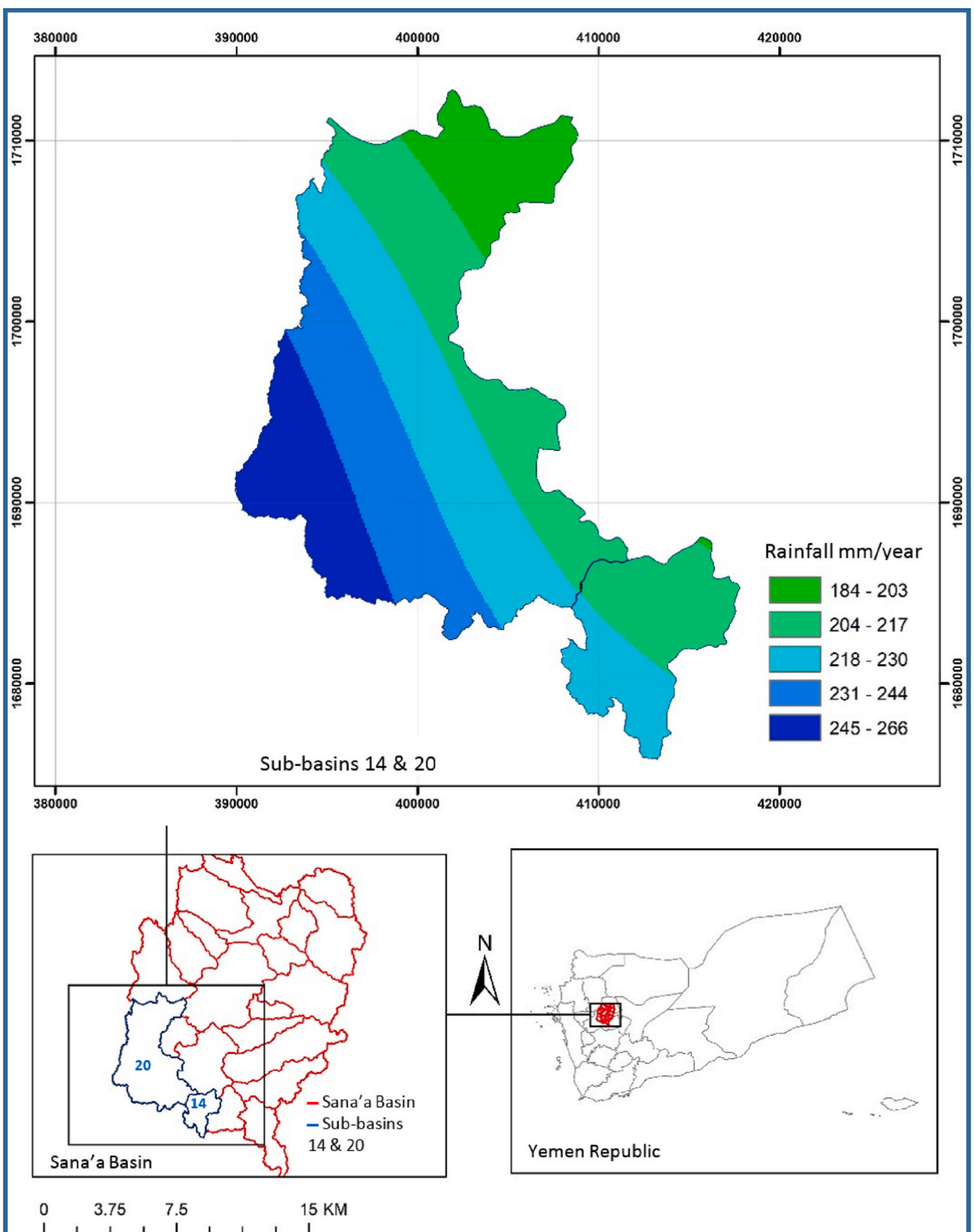

Fig. 1. Study area.

downstream area meaning that RWH is more important here.

2.2. Framework development

In this study, the current status of indigenous RWH systems and related factors were identified through three independent data sources (Table 1): (i) face-to-face in-depth surveys with a local group consisting of water users, farmers, and community leaders; (ii) key informant interviews with academics, water and agriculture experts, and engineers; and iii) rough set analysis using data on the characteristics of 22 existing RWH systems of the so-called *Birak* type—roofless RWH ponds commonly found in the study area (Fig. 2).

2.2.1. Interviews and questionnaires

Our questionnaire covered several topics such as the interviewees' experience and views on indigenous RWH systems, the importance of farming to their livelihoods, and the current operational status of Birak systems. Participants were selected from different areas in the selected sub-basins using a proportionate sampling technique. The detailed questionnaires for both groups (locals and key informants) are provided in Supplementary Materials 1.

A total of 17 potential factors comprising technical, institutional, socioeconomic, and climatic elements were selected from a literature review, researchers' experiences, meetings with RWH specialists and managers, and a pre-testing sample of ten local experts and 20 local farmers. Table 2 shows the full list of factors. These 17 factors were part of the questionnaire in which locals were asked the dichotomous "yes/no" question as to whether or not the particular factor played a role in the abandonment of the indigenous RWH. The key informants were asked to judge the degree of impact of the different factors as either very high, high, medium, low, very low, and no impact (Table 3). This scaling method is commonly used to understand categories that do not have a clear quantifiable aspect such as happiness or satisfaction. Therefore, it was considered a suitable method to assess the level of impact.

2.2.2. Field study and measurements for selected systems

Twenty-two *Birak* RWH systems were visited and data on the technical and socioeconomic aspects were collected. *Birak* systems are used for several different purposes but are mainly used for non-drinking domestic purposes and livestock. The selected systems included both working and abandoned ones. To identify the factors that were decisive in determining the continuation or abandonment of these specific systems, and to assess their importance, we used rough set analysis. By using a literature review, along with a discussion with experts and field information collected by the owners and/or users of the RWH system, a list of eight main system attributes were derived that could have potentially had an impact on whether or not they had been abandoned. The local user(s) of the systems were asked to confirm the selected system attributes and operational status. The final set of attributes used in the rough set analysis is shown in Table 4.

2.2.3. Rough set analysis

Though the rough set theory was found by Professor Pawlak (1982), it has attracted increasing attention among researchers in recent years (Qinghua et al., 2016). Rough set analysis is a mathematical method used to synthesize an approximation of concepts out of data that allows information classification (Liang and van Dijk 2015). It deals with imprecise, inconsistent, incomplete information and knowledge (Pawlak, 1982). Based on rough set theory, application research focuses mainly on attribute reduction and provides several new data mining methods. It is also able to simplify academic communication and promotes the development and application of rough sets. The rough set theory has been used in different fields such as economics, medicine, software engineering, prediction and control, and algorithm research. However, this method has rarely been applied to water studies (Liang and van Dijk 2015; Qinghua et al., 2016).

During the fieldwork, qualitative data on the system attributes (F1–F8) and operational status (D) of the 22 selected systems (S1–S22) were collected through interviews with local users. The characteristics (F1–F8) were codified as 1, 2, 3, or 4, as shown in Table 4. Three operational statuses (D) were identified: abandoned, continuous, and intermittent. "Abandoned" means that the system is no longer operational and is given a score of 1; "continuous" means the system is still being used regularly, continuously and is given a score of 2; while "intermittent" means that the system is not in constant use and is given a score of 3. After codifying the system attributes (F1–F8) and operational status (D), we obtained a data matrix of the 22 systems (S1–S22), which is shown in Table 5.

The rough set analysis method aims to determine the causal links between the system attributes (F1–F8) and the operational status (D). It searches for the core attributes that cannot be removed from the information system without creating a visible or discernible effect. All attributes that create a discernible relationship are kept as part of the core, while attributes that lead to the same operational outcomes in all 22 systems (i.e. that can be removed without creating discernibility) were removed from the analysis as they cannot be judged by this method. Consequently, system attributes F1 and F5 were removed as they resulted in the same operational status for all the systems and would have had no impact on the analysis.

In the next step, sets (SE) were created for each system attribute. For instance, for F8 ("locals have doubts regarding rainwater quality") systems S1, S5, S11, S15 had the same score (1), while there were no doubts regarding rainwater quality in the other 18 systems (F8 = 2).

Assuming that the 22 RWH systems (S1–S22) and all system attributes (F1–F8) belong to a set (SE), the following sub-sets (SE/F) can be classified:

SE/F2 = {{S7 ⋯S10, S13, S16, S29, S20}, {S1 ⋯S6, S11, S12, S14, S15, S17, S18, S21, S22}}

SE/F3 = {{S4, S13, S14, S18}, {S1, S2, S3, S5 ⋯ S12, S15 ⋯S17, S19 ⋯S22}}

SE/F4 = {{S3, S5, S7, S18, S19, S21, S22}, {S1, S2, S4, S6, S8, S9, S10, S13, S16, S20}, {S11, S12, S14, S15, S17}}

SE/F6 = {{S3, S15}, {S2, S11, S19}, {S1, S4 ⋯ S10, S12 ⋯ S14, S16 ⋯ S18}, {S20 ⋯ S22}}

SE/F7 = {{S1 ⋯ S6, S18}, {S7 ⋯ S10, S15, S16, S19 ⋯ S22}}

SE/F8 = {{S1, S5, S11, S15}, {S1 ⋯ S4, S6 ⋯ S10, S12 ⋯ S14, S16 ⋯ S24}}

In the next step, the systems S1–S22 were classified into sub-sets according to operational status (D1 = abandoned; D2 = continuous operation; D3 = intermittent operation).

SE/D = {{S7, S10 ⋯ S15, S16, S19 ⋯ S22}, {S1 ⋯ S6, S18}, {S11 …. S14, S17}} With D1 = {S7, S10 ⋯ S15, S16, S19 ⋯ S22}; D2 = {S1 ⋯ S6, S18}; D3 = {S11 …. S14, S17}

Assuming attribute F_i is the critical factor affecting the operational status, the D_j, linkages can be identified as follows:

$(SE/F_i) \cap (SE/D) = D_j$ (i = 1, 2, 3 …. 8. j = 1, 2, 3)

Using the aforementioned equations, the analysis yielded three

Table 1
Sources of study data.

Sources of study data	Survey of local users	Key informant interviews	Rough set analysis
Description	Water users, farmers, and community leaders	Scientific and knowledge group	Birak RWH systems
No.	100	65	22

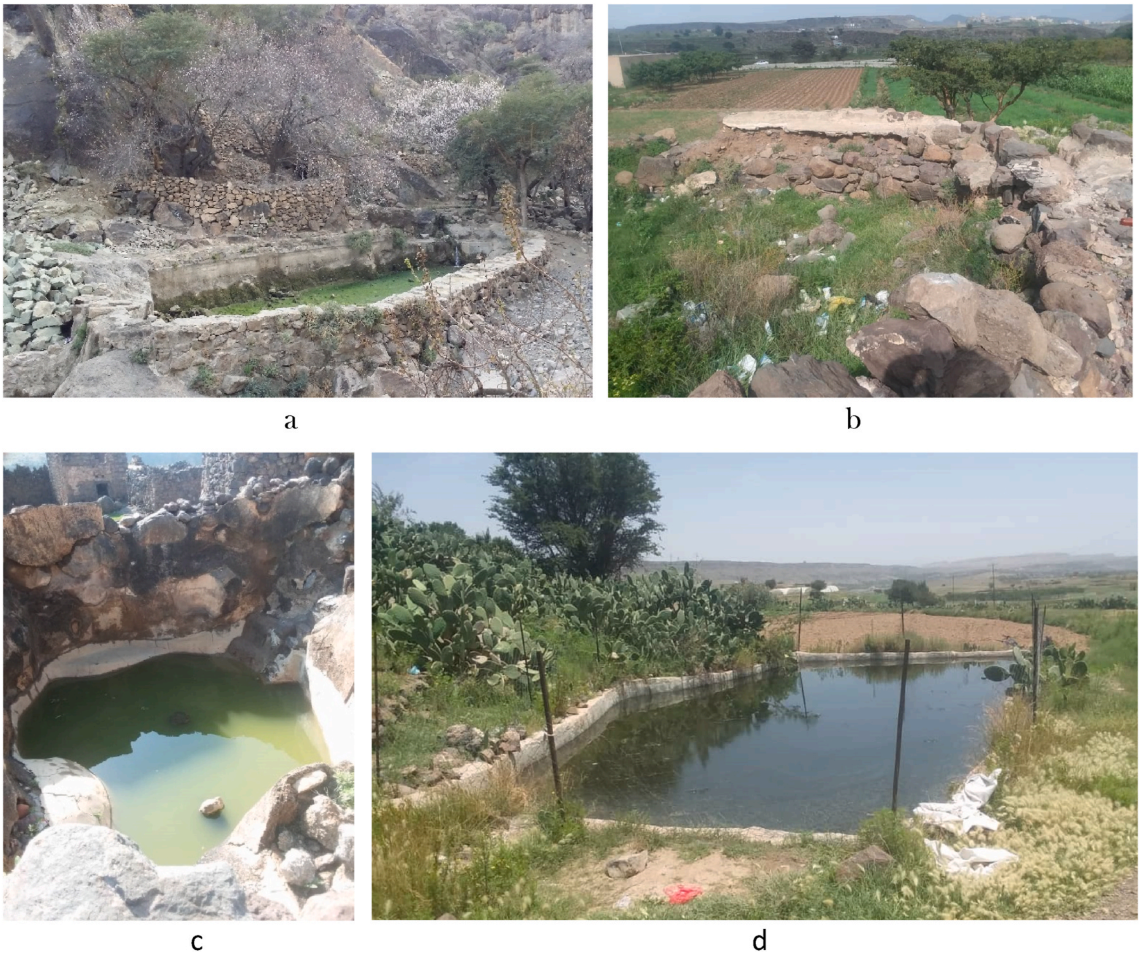

Fig. 2. Photographs of the study areas (a) Al-Athuam (b) Al-Humais (c) Al-Husn (d) Bait Al-Faqih.

Table 2
A list of the potential factors affecting the abandonment of indigenous RWH systems, to be completed by local respondents.

#	Factors	Yes	No
1	Availability of other water sources and technologies (such as groundwater, water tankers)		
2	Low cost of water from other sources		
3	The effort and high cost of building and maintaining indigenous technologies (compared with the availability of newer, cheaper sources such as pipes, etc.)		
4	Climate factors (changes in precipitation)		
5	Loss of ancient knowledge and techniques regarding water harvesting		
6	The relatively limited capacity of the RWH systems compared with the increased demand for water due to growing populations		
7	Lack of competent workforce		
8	Availability of alternative food sources (imported food and grain from abroad)		
9	Weak cooperation and loss of social cohesion between local populations (indigenous cooperatives)		
10	Urbanization (new projects and modern infrastructure such as roads, etc.)		
11	Conflict over ownership of water and soil, and means of harvesting systems		
12	Internal and external migration		
13	Low economic yields and return of rain-fed agriculture		
14	Lack of maintenance for indigenous rainwater harvesting technologies		
15	State neglect of rainwater harvesting projects, and lack of awareness and support for farmers		
16	Loss of justice and weak state authority (weak state power)		
17	Rainwater quality		

Table 3
List of potential factors to be completed by key informants.

#	List of factors (1–17)	Degree of impact					
		Very High 5	High 4	Medium 3	Low 2	Very low 1	No impact 0
1	……….						
2	…..						

decision rules:

R1: (F3, 3) ∩ (F7, 2) → (D, D1): All community-owned systems that cannot capture sufficient water to meet demand have been abandoned.

R2: (F2, 2) ∩ (F7, 1) → (D, D2): All systems with sufficient water throughout the year, in which users prefer surface water over groundwater, are functioning continuously.

R3: (F7, 3) → (D, D3): All systems that only have a seasonal sufficiency of water are operated intermittently.

3. Results and discussion

3.1. Field survey and key informant interviews

More than 96% of the respondents in this study, reaffirmed that indigenous RWH techniques were continuing to decline and deteriorate. Our analysis revealed that several factors have contributed to this decline but have differing levels of impact. Government neglect, lack of maintenance, and availability of groundwater resources (Factors 15, 14, and 1 in Table 2) were highlighted by farmers as the three main factors

Table 4
Description and coded values of system attributes potentially affecting the operational status of indigenous RWH systems.

#	System attributes	Characterization and Coded Values (Numbers)
1	Availability of groundwater	*1: Available* *2: Not available*
2	Users' perception of RWH systems compared with groundwater sources	*1: Negative* *2: Positive*
3	Ownership	*1: Private* *2: State-owned* *3. Community-owned*
4	Size of System	*1: Small* *2: Middle* *3: Large*
5	Subsidies for operation and maintenance	*1: Yes* *2: No*
6	Water use	*1: Domestic* *2: Irrigation* *3: Domestic and irrigation* *4: Other*
7	The adequacy of the system for covering needs	*1: Sufficient throughout the year* *2: Not enough* *3. Sufficient seasonally*
8	Doubts regarding rainwater quality	*1: Yes* *2: No*
##	Current operational status	*1: Abandoned* *2: Continuous* *3: Intermittent*

Table 5
Codified data matrix for RWH systems S1–S22 with the system attributes (F1–F8) and resulting operational status (D).

F S	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	D
S_1	1	2	3	2	2	4	2	1	1
S_2	1	2	3	1	2	4	2	2	1
S_3	1	2	3	1	2	1	1	2	2
S_4	1	2	1	2	2	3	1	2	2
S_5	1	2	3	1	2	3	1	1	2
S_6	1	2	3	2	2	3	1	2	2
S_7	1	1	3	1	2	3	2	2	1
S_8	1	1	3	2	2	3	2	2	1
S_9	1	1	3	2	2	3	2	2	1
S_{10}	1	1	3	2	2	3	2	2	1
S_{11}	1	2	3	3	2	2	3	1	3
S_{12}	1	2	3	3	2	3	3	2	3
S_{13}	1	1	1	2	2	3	3	2	3
S_{14}	1	2	1	3	2	3	3	2	3
S_{15}	1	2	3	3	2	1	2	1	1
S_{16}	1	1	3	2	2	3	2	2	1
S_{17}	1	2	3	3	2	3	3	2	3
S_{18}	1	2	1	1	2	3	1	2	2
S_{19}	1	1	3	1	2	2	2	2	1
S_{20}	1	1	3	2	2	4	2	2	1
S_{21}	1	2	3	1	2	3	1	2	2
S_{22}	1	2	3	2	2	2	1	2	2

that had the highest negative impact on indigenous RWH systems. Taking the weighted values of the five categories of impact (very high, high, medium, low, and very low), both the experts and professionals selected the same factors as the farmers (15, 14), but disagreed on the importance of groundwater availability (Factor 1), choosing instead low economic yield and returns of rain-fed agriculture (13). The government's neglect of RWH projects was identified as having the highest impact by all respondents (see Fig. 3, Fig. 4, and Table 6). Rainwater quality was deemed to have the lowest impact, followed by the cost of other water sources.

3.2. *Results of the rough set analysis*

The *Barik* systems visited for this study were either abandoned, operated continuously, or operated intermittently. From the rough set analysis, three rules were derived. The first rule was that when the system is public or community-owned but does not meet demand, the system is abandoned. The second rule is that the system is used continuously if users' perception of traditional systems is positive compared with groundwater sources, and when it is possible to obtain sufficient water from this system. The third rule is that the system is used intermittently when water is not always sufficiently available. Groundwater was available at all the systems, so system attribute F1 could not be examined using rough set analysis. The perception of groundwater is linked to different operational outcomes; hence, this system attribute (F2 in rule 2) was the only way that this method could judge the impact of groundwater on the operational status of *Barik* systems. The analysis showed that people at some locations preferred harvested rainwater over the more expensive groundwater (Rule 2).

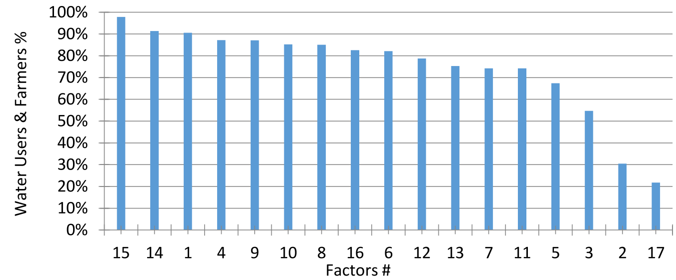

Fig. 3. Factors affecting the use of indigenous RWH technologies (water users' and farmers' perspectives).

Table 7 summarizes the rules, conditions, current status, and systems concerns. Although the data collected are for one just type of RWH system (i.e. *Birak*) and were collected from only two sub-basins, the results were confirmed by national experts and professionals.

3.3. *Overall results*

Three institutional, technical, and socioeconomic factors can be considered as decisive in the continued use of indigenous RWH systems or their abandonment (Table 8). These interrelated factors are the government's neglect of RWH projects (15), the availability of groundwater (1), and a lack of maintenance (14). Two factors are considered to have a very low impact: rainwater quality and the cost of other water sources.

3.3.1. *The role of government*

Farmers as well as key informants considered the government's neglect of RWH projects to be the main reason for their decline. Mismanagement of groundwater resources led them becoming increasingly depleted and exacerbated the degradation of indigenous RWH technologies. Because of a lack of enforceable laws, wealthy people in rural areas invested heavily in digging wells to increase their income, resulting in an uncontrolled expansion of groundwater extraction. Key informants lamented the lack of interest from the government and donors in water-harvesting projects, as well as the lack of any comprehensive strategy on sustainable water use by promoting RWH and reviving and modernizing indigenous techniques. By contrast, countries such as Morocco, Tanzania, and India, and even cities such as Texas, San Francisco, and Delhi, have developed their own RWH manuals and strategies (Allen et al., 2016; Brown et al., 2005; El Hamoumi et al., 2019; Omondi et al., 2009; Rumi, 2020; Shri et al., 2002). None of the studied RWH systems received direct or indirect subsidies from the state, while groundwater use, by contrast, is heavily subsidized and promoted. In Yemen, there are more than 40 authorities who manage and supply groundwater to local communities. By contrast, there are very few official authorities and actions concerned with indigenous RWH techniques. However, there is the Social Fund for Development (SFD) and

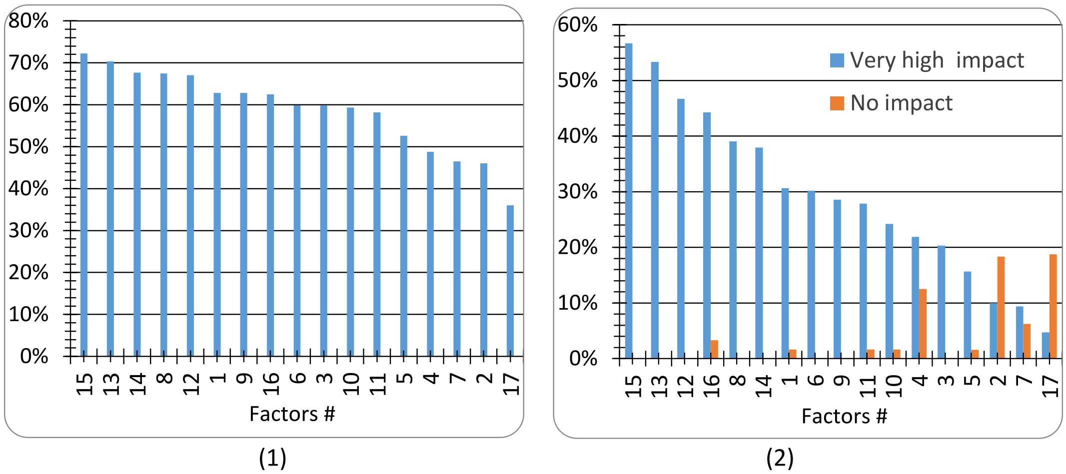

Fig. 4. Experts and professionals' perspectives on different factors affecting the use of indigenous RWH technologies: (1) Weighted values (2) Very high impact and no impact categories.

Table 6
Perspectives of locals and knowledgeable groups on factors affecting the use of indigenous RWH.

100 Farmers	65 Experts & professionals
- Factors with the highest impact	- Weighted values
15. Government neglect of RWH projects (98%)	15. Government neglect of RWH projects (72%)
14. Lack of maintenance (91%)	13. Low economic yields and returns of rain-fed agriculture (70%)
1. Availability of groundwater resource (91%)	14. Lack of maintenance (68%)
	- Very high impact category
	15. Government neglect of RWH (57%)
	13. Low economic yields and returns of rain-fed agriculture (53%)
	12. Internal and external migration (47%)
Factors with the lowest impact (Farmers, Experts, and Professionals)	
17. Rainwater quality	
2. Low cost of water from other sources	

Table 7
Rules derived from the rough set analysis.

Rule	System Attribute	Operational Status	Systems
1	The system is public, or community-owned and provides insufficient water during the year	Abandoned	S_1, S_2, S_7, S_8, S_9, S_{10}, S_{15}, S_{16}, S_{19}, S_{20}
2	The system users prefer harvested water over groundwater. The system provides sufficient water throughout the year	Used Continuously	S_3, S_4, S_5, S_6, S_{18}, S_{21}, S_{22}
3	Sufficient water only seasonally	Intermittent	S_{11}, S_{12}, S_{13}, S_{14}, S_{17}

the Public Work Project (PWP), which implement small RWH structures to collect rainwater for irrigation and domestic use and replenish groundwater supplies (Fanack, 2019). Nevertheless, these development activities are still far from sufficient to counteract the declines that have occurred and are still occurring in the indigenous RWH systems.

The absence of a strategic vision, development policies, and sufficient scientific research are all because of a lack of investment by the Yemeni government. In rural areas, where the majority of people live, strategies for developing the countryside and improving local livelihoods, even in terms of basic services, are still lacking. Additionally, although RWH is mentioned in the National Water Strategy (NWSSIP), the necessary actions are still lacking.

3.3.2. Groundwater availability and accessibility

Groundwater availability was selected by farmers as one of the main factors affecting the use of RWH systems. In the past, the main motivation for the development and innovation of RWH technologies were water scarcity and food shortages. RWH techniques were feasible solutions that provided users with sufficient quantities of water for drinking and food production, often in the face of a complete lack of alternative options. Nowadays, more options have become available, including groundwater supplies, which provide people with a cleaner, more reliable water source.

Groundwater was available in varying levels at all the visited study sites. In remote areas where groundwater is scarce or expensive, local people prefer RWH technologies over groundwater sources. This was confirmed by farmers when asked their opinion on RWH practices compared with groundwater abstraction. The users of abandoned or partially working RWH systems, by contrast, preferred groundwater to harvested rainwater. RWH systems were viewed more positively in areas lacking cheap and accessible groundwater.

There is a clear link between government policy and groundwater depletion. During the 1970s and 1980s, the government focused on food security by promoting the use of groundwater for irrigation. The government offered loans to Yemeni farmers for buying pumps and drilling wells at very favorable interest rates (9–11%, at a time when commercial rates were 50–60%). In 1990, the government-subsidized diesel to a quarter of the international price level. As a result, unregulated well-drilling soared, particularly among wealthier farmers who were able to invest in wells. Many indigenous RWH systems were abandoned in favor of these tube wells (Ward, 2014; Varisco, 2019).

Historically, rainwater has always been the main source of irrigation and food production in Yemen. However, farmers today rely upon groundwater to increasingly large extents, which was not the case just decades ago. The introduction of diesel-operated pumps and tube well drilling technology has enabled groundwater to be extracted significantly above recharge levels. This has led to the expansion of agricultural areas—as the irrigated area in Yemen has increased from 37,000 ha in the 1970s to more than 400,000 ha in the 2000s—but also to the depletion of aquifers. During the same period that as irrigated areas increased 11-fold, the area supporting rain-fed agriculture declined by 30 percent (Closas and Molle, 2016).

However, due to the ongoing conflict in Yemen, the fuel required for the pumps has become scarcer and much more expensive. Piped water supply in some places has become more erratic due to the lack of energy or damaged infrastructure. Consequently, many people have returned to their previously abandoned RWH practices (Aklan et al., 2019). Those with sufficient financial means have begun using solar pumps, as Yemen

Table 8
Decisive factors affecting the use of indigenous RWH systems.

Factors	Category	Farmers' perception	Key informants	Rough set analysis	Level of impact
Government neglect of RWH projects	Institutional	x	x		Very high
Availability of groundwater	Technical	x		x	
Lack of maintenance for indigenous RWH projects	technical	x	x		
Ownership of RWH systems	Socioeconomic			x	High
The limited water storing capacity of indigenous RWH systems compared with the needs of an increased population	technical			x	
Low economic yields and returns of rain-fed agriculture	Socioeconomic		x		
Internal and external migration	Socioeconomic		x		
Availability of alternative food sources	Socioeconomic		x		

has abundant sunshine. However, although solar energy is a low-carbon renewable source, it can be a double-edged sword. Solar-powered groundwater pumps are now spreading rapidly throughout Yemen despite the ongoing conflict. The incidence of solar-powered irrigation in the Sana'a Basin alone is increasing at a rate of more than four percent annually. If this trajectory were to continue, all diesel-powered pumping systems would be replaced by solar pumps within 15 years, or in as little as seven years if Yemen's socio-political and security situation were to stabilize (Aklan and Helen, 2021). However, as solar energy's pumping costs are far lower than diesel for each additional unit of water, its overall impact on groundwater may be far worse than diesel pumps in the long term (Aklan et al., 2019).

3.3.3. Lack of maintenance, ownership, and size

The results of this study showed that the lack of maintenance is among the main factors affecting the continued use of RWH systems. This is also the case for many indigenous RWH systems in the Arabian region (Abdo and Eldaw, 2004; Oweis et al., 2004). The ownership and size of the systems play an important role in their maintenance. Users indicated that public and community-owned systems are only repaired and maintained every two or three years, if at all, while privately owned systems are maintained every year or season. This means that community-owned systems are more likely to be abandoned. The rough set analysis revealed that all privately owned systems studied were still in use either continuously or intermittently. By contrast, all the community and public systems studied had been abandoned, even the larger ones (Table 5).

Many of the publicly owned RWH systems were ignored by local farmers because they were either too far away from residential areas or they were small and unable to provide sufficient water to cover local needs, including systems connected to *ghils* (springs). Indigenous RWH systems require regular maintenance by periodically removing alluvial sediment (e.g., fine sand, silt, and clay) and organic materials such as bacterial slime and algae. Key informants noted that Water User Associations (WUAs) and agricultural associations were relatively new in Yemen and had not taken root yet. Therefore, more active involvement and participation by local communities in RWH systems is vital at all stages to avoid any adverse interventions that could affect them. It could also give locals a sense of ownership and the impetus to conserve and participate in the operation and maintenance of all RWH systems, particularly the public ones.

The lack of maintenance is also linked to government neglect. Discussions with local stakeholders revealed that very few RWH systems that had fallen into disrepair were being repaired by the government. Also, the government has not yet played a facilitating role in urbanization, development, road construction, or any creative local solutions to conserve groundwater.

3.3.4. Socioeconomic shifts

The key informants pointed out several interrelated socioeconomic factors that adversely affected the continuous use of RWH systems, including increasing population, the limited capacity of RWH projects, stagnating agricultural productivity, the availability of imported food, and increased rural-urban migration. Our study revealed that 92% of the farmers we interviewed had to either partially or fully rely on food imports market to cover their basic needs. Only a few families (8%) still relied on subsistence farming to cover their basic needs, mostly in households with less than ten people (Fig. 5).

Urbanization, development, and road construction are other reasons that encouraged rural-urban migration and caused a shift in agricultural practices in general and a decline in rainwater harvesting systems in particular. Many locals shifted away from agricultural activity to other service sectors as a way of boosting their livelihoods and income. New job opportunities in other sectors will mean it will be easier and cheaper to obtain imported food.

Continuing urbanization and road construction in rural and urban areas change the natural topography by covering increasing large areas of arable land. This affects groundwater recharge rates, the hydrology of streams and affects many RWH systems. For example, since Sailah Wadi in Sana'a city was paved the amount of runoff has increased. This changed the topography of the valley, increased the risk of flash flooding, and affected the runoff infiltration to underlying layers. Connecting the sewage, drainage systems to some hydrology of streams (wadies) caused pollution and decreased the farmers' trust in the runoff/flood water. Some 20% of abandoned RWH were cleared for new buildings or were far away from residential areas. With the improved availability of groundwater as an alternative source, rainwater quality becomes more of a concern as it can affect the use of RWH systems even for irrigation, as shown by Liang and van Dijk (2015). However, the rainwater quality in this study was of lesser concern according to stakeholders because most of the RWH systems are used for non-drinking purposes.

4. Conclusions and recommendations

Indigenous RWH systems are in long-term decline, with government neglect identified as the most significant factor, followed by groundwater availability and lack of maintenance. The limited capacity of systems, the low economic yields of rain-fed agriculture, increased rural-

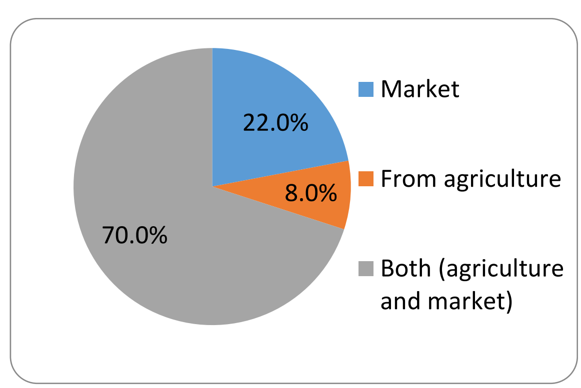

Fig. 5. Food sources.

urban migration, and the availability of livelihood alternatives are also considered factors that impact the use of indigenous RWH systems. However, given the alarming decline in groundwater levels, the dependency on imported fuel, and import disruption due to the ongoing war, calls to revive RWH systems are growing.

While combined action from government, local communities, and development actors is essential, the role of the state was identified as a major variable in the revival of indigenous RWH systems. By providing subsidies for drilling and operating wells, the government is actively promoting the use of groundwater at the expense of RWH, which receives little government support. Therefore, there is a need for a clear RWH strategy and policy in Yemen. This includes raising awareness, harnessing support from local communities, and revitalizing state and community-owned RWH systems. The assessment of different water resources in different areas and the adoption of the necessary supporting policies, regulations, and schemes for engaging and prioritizing rainwater sources among other sources including scarce groundwater resources are essential elements for such a strategy.

Although this study relied on the perspectives of many experts and professionals from different sectors, the farmers who were interviewed, as well as the study areas themselves, were from the upper part of the Sana'a Basin, where rainfall is relatively higher and groundwater is less accessible. Further studies on different RWH systems in different areas, particularly in downstream areas, will add insight to this study. As mentioned, the field study was conducted in the Sana'a Basin despite the ongoing conflict and faced many security issues. The study team's movement was restricted, and they were often stopped and interrogated several times at the frequent checkpoints.

The results of this study are genuine and can provide scientific guidelines for decision-makers and water managers. Our results have demonstrated the powerful capabilities of rough set analysis in handling factors affecting the use of indigenous RWH systems, particularly in areas where data is scarce. Rough set analysis can help decision-makers at various governmental levels in combating water problems including water scarcity and groundwater depilation. The framework presented in this study is generic and can easily be replicated in other parts of the country as well as in other dry, limited-data regions in order to analyze different water problems.

CRediT authorship contribution statement

Musaed Aklan: Conceptualization, Investigation, Methodology, Data curation, Writing – original draft, Writing – review & editing. **Charlotte de Fraiture:** Supervision, Validation, Writing – review & editing. **Laszlo G. Hayde:** Supervision, Writing – review & editing. **Marwan Moharam:** Conceptualization, Investigation, Methodology, Writing – original draft.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jaridenv.2022.104765.

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