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Indicator assessment of groundwater resource sustainability: Using the framework of socio-ecological systems in Hamedan - Bahar Plain, Iran

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ABSTRACT

Study area: Iran.
Study focus: Hamedan-Bahar plain is one of the important plains in the west of Iran, which is facing a shortage of water resources and excessive extraction of groundwater resources. The purpose of this article is to identify and evaluate the status of sustainability governance indicators using the knowledge of local experts, which can be an effective step towards the sustainable management of groundwater resources. In this paper, we apply Ostrom's Social-Ecological Systems Framework (SESF) as a diagnostic tool with 52 indicators to assess the sustainability of groundwater resources.
New hydrological insights for the region: Based on key informant interviews with local experts and stakeholders, we use the TOPSIS technique and the Shannon Entropy methodologies to weigh and rank indicators influencing sustainability. Findings revealed that the indicators within the category Resource Systems (RS) and Resource Units (RU) with values of 0.74, and 0.70, are the most stable contributing factors to local sustainability, respectively. In contrast, the Governance System (GS), Actor (A), and Interaction (I) first-tier variables were evaluated as less stable, along with Outcomes (O). This suggests that social factors and diverse outcomes may need further attention in the region to ensure management and policy development that can better enable sustainable outcomes. This analysis also demonstrates the usefulness of a comprehensive science-based framework for organizing, analyzing, and presenting a wide range of complex information to inform policymakers and planners.

1. Introduction

Sustaining groundwater resources is essential for human well-being, economic development, and environmental protection in many water-scarce regions, particularly those dependent on local agriculture (Qasemipour and Abbasi, 2019; Karimi et al., 2024). However, groundwater quality and quantity are often challenged by population growth, urban sprawl, agricultural expansion, and

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economic growth in recent decades (Stevenazzi, 2017; Yan et al., 2018; Xu et al., 2019; Liu et al., 2020; Zeydalinejad et al., 2023). Groundwater remains a viable option because it is often cheaper, more convenient, and less vulnerable to pollution than surface water. Therefore, it is commonly used for public water supplies (Luker, 2017). More than half of the global urban population relies on groundwater to meet their basic needs (Mishra et al., 2021), but many challenges remain for governing towards sustainability. This is because the amount of groundwater available is often unknown and difficult to measure, and many people are removing groundwater from different locations at unknown rates of extraction. Challenges for governing groundwater have been formally studied going back to the 1960s, where commons governance pioneer Elinor Ostrom – and later Nobel Prize recipient for her research on the commons - examined groundwater governance challenges in Los Angeles, California (Ostrom, 1990). This exacerbates the collective action challenge of governance, which often lacks a feedback mechanism on the effectiveness of institutional development efforts (Aspril-la-Echeverria, 2021; Majidipour et al., 2021). When the use and dependency on groundwater increases, more challenges and problems are likely to arise given their common-pool resource characteristics that make excluding users difficult among high competition for few limited resources. This makes the need for establishing institutions and property rights critical for sustainability such as who has rights to own, use, access, protect, and develop institutions for water resources (Bogardi et al., 2021; Eman and Meško, 2021; Katz, 2021). The lack of a clear allocation of water resources in various nations has posed challenges to human security and development during times of scarcity (Bai et al., 2015; Feng et al., 2020). Effective governance, which focuses on long-term sustainability, must consider these potential risks and uncertainties (Petrakis et al., 2023). Also, it should recognize the characteristics of water as a common-pool resource, necessitating collaborative efforts and various rights allocation approaches (such as common property, state, or private) to guarantee equitable access, usage, and fair distribution based on need and rationale (Tucker et al., 2023).

Numerous frameworks have been developed in the agricultural sector to facilitate the analysis of the preservation and sustainability of agricultural resources, food security, and ecological balance (Han and Niles, 2023). These frameworks highlight the importance of considering environmental, cultural, social, and economic dimensions, such as SAFA, RISE, MASC, LADA, SMART, DPSIR, etc. (Brown et al., 2023; Malmir et al., 2022). By integrating these dimensions and choosing appropriate frameworks, it becomes possible to make science-based assessments of the overall sustainability of agricultural practices, which can inform long-term economic development that is also environmentally sustainable (Alaoui et al., 2022).

A substantial amount of literature has examined water and groundwater sustainability issues, with more recent literature focusing on integrated social-ecological factors for analysis (Elshall et al., 2020; Gleeson et al., 2020; Zwarteveen et al., 2021). For example, in the study of Bathaei and Štreimikienė (2023), they introduce 8 indicators in three social, economic, and environmental dimensions in order to assess sustainability in the agricultural sector, which include technology, market access, price, pollution, farm structure, soil, product quality and farmers' rights. These factors, as well as others such as water scarcity, climate change, and increasing demand, have become critically important components for comprehensive sustainability assessments that take into account ecological restoration, economic development and social security guarantees (Guo et al., 2023; Bozorgzadeh and Mousavi, 2023). Furthermore, other factors such as the water limits related to impacts on ecosystems, economies, and human health, can help ensure prosperous agricultural production and a safe water supply (Troy et al., 2023). To increase resilience and implement integrated management of water resources, different methods and frameworks can be used to assess watershed conditions and select indicators for the sustainability of water resources systems (Borden and Goodwin, 2022; Hosseini et al., 2019). After collecting a wide range of data guided by these comprehensive frameworks, strategic planning can be informed by using multi-criteria decision-making models to help rank regional management options for agricultural water management, promoting sustainable water management practices in large-scale water resource systems (Radmehr et al., 2022).

Overall, research shows that in the management of small-scale watersheds, the balance between ecological, social, and economic factors is very important for sustainability (Ananda et al., 2023). Also, various frameworks have been proposed to investigate the complexity and sustainability of socio-ecological systems more generally. The most widely used and cited framework is the Social-Ecological System Framework (SESF) (Ostrom, 2009; McGinnis and Ostrom, 2014). In this study, agricultural sustainability indicators have been examined based on the SESF framework, taking into account socio-environmental and economic aspects. This builds on similar previous research such as from Di et al. (2022), who showed that water scarcity in China is a complex social, economic, and ecological system whose management is influenced by various factors such as climate change, geographical location, water resources, diverse users, and unbalanced development policies. Ndlovu et al. (2022) argue that water problems are not separate from other social and ecological problems; they are related to social, economic, legal, environmental, and political issues that need to be considered when establishing governance arrangements. Montenegro and Hack (2020) found that multi-level water governance in Nicaragua faces challenges of investment, budget restraints, lack of collective choice rules and low knowledge in resolving disputes are key problems. Lastly, Villamayor-Tomas et al. (2014) shows how applying the common-pool resource theory and the SESF can help unpack the factors shaping governance challenges in the large Rhine River watershed.

In social-ecological systems such as groundwater, gathering data for comprehensive assessments remains challenging. Developing and monitoring indicators to inform management options can be difficult, often leaving a limited set of social and ecological factors to analyze (Pandey et al., 2011). Including stakeholders and local knowledge can help bridge knowledge gaps and ground an analysis in the local context. Harnessing local knowledge is increasingly used as an effective methodology because it is grounded in the local social-ecological context, inclusive, and often the only way to conduct rapid assessments in data-scarce regions by drawing on local stakeholder inputs who have extensive insights over time into key issues (Tengö et al., 2017; Camara-Leret and Dennehy, 2019). Furthermore, using local experts' knowledge from, for example, resource users and expert practitioners, to inform sustainability assessments and governance decision-making is increasingly championed as an inclusive knowledge co-production strategy to improve outcomes (Sterling et al., 2013; Tengö et al., 2017).

To our knowledge, Ostrom's framework has not been used in the studied area, which can offer new contextual insights. The findings in this study can inform and offer comparative insights for the study of groundwater and others commons in different contexts, as well as offer locally tailored insights for management and policy. Based on highly contextualized local stakeholder and expert knowledge inputs, this study helps analyze the current groundwater sustainability situation and the challenges ahead in the sustainable management of underground water resources in Bahar Hamedan Plain. Finally, this research, with its comprehensive and quantitative approach, provides an innovative methodological approach that has not been utilized or explored before in current applications of the Ostrom framework in any context (Nagel and Partelow, 2022).

So far, Ostrom's socio-ecological framework has not been used in the studied area. Therefore, in this research, the results that will be obtained can be used in other areas and can be used as a useful tool for organizing, analyzing, and presenting information to policy makers and planners. This study is done by providing knowledge and evidence. Experience can help experts to better understand the real situation and the challenges ahead in the sustainable management of underground water resources in Bahar Hamedan Plain. Finally, this research, with its comprehensive and quantitative approach, provides an innovative perspective for the sustainable management of underground water resources in different social, ecological, and environmental dimensions, etc.

Hamadan province ranks fourth in the country in terms of agriculture. But in recent years, it has faced problems due to climate changes and a sharp decrease in rainfall, and excessive extraction of groundwater resources. Hamadan-Bahar plain one of the important plains in west Iran, is facing a shortage of water resources and the over-harvesting of groundwater resources. In addition to the problems of over-harvesting, there are other challenges as more pressure on groundwater resources (Llamas and Custodio, 2002; Ostad Ali-Askari et al., 2018, 2019), creating environmental stresses such as the drying of springs (Taheri et al., 2015a, 2015b, 2016), salinity of aquifers (Bagheri et al., 2019; Panagopoulos 2021a), land subsidence (Karimi and Taheri, 2010; Rezaei et al., 2021), sinkhole formation (Taheri et al., 2015b, 2019, 2021). Therefore, it is necessary to pay attention to the sustainability and governance of groundwater resources in this region to improve the current and future situation.

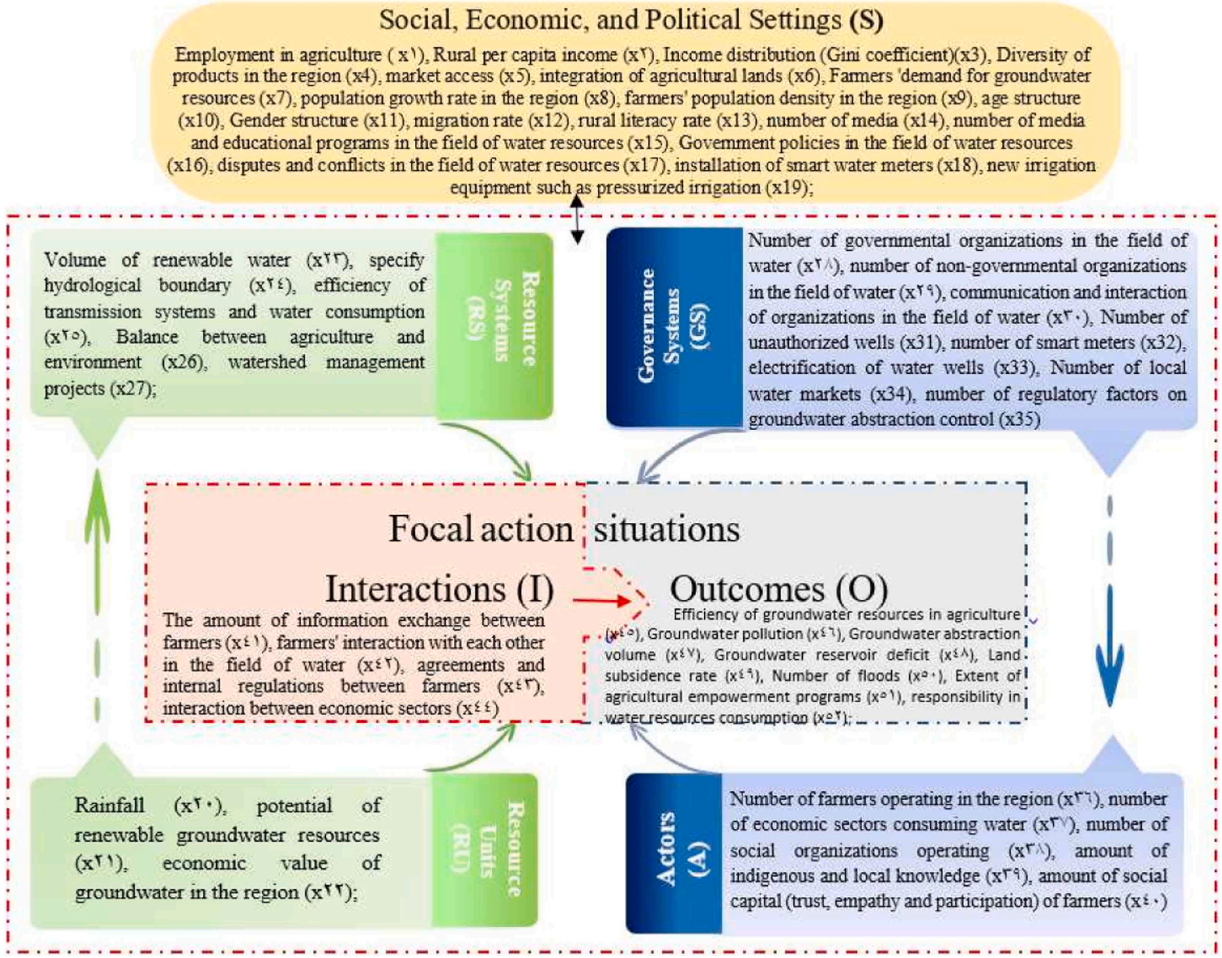

Fig. 1. The social- ecological systems framework (SESF), showing the first-tier variables and their conceptualized interactions (McGinnis and Ostrom, 2014).

2. Understanding groundwater sustainability with the Social-Ecological Systems Framework (SESF)

Natural resource sustainability requires an understanding of the complexity of integrated systems (i.e., social, biophysical, economic) and their interactions (Cumming et al., 2013; Spiegelaar, 2023). Historically, many natural resource management approaches have failed due to fragmented, isolated, or limited disciplinary perspectives shaping decision-making (Holling and Meffe,1996; Holling, 2003; Bergstrom et al., 2021). Over the last few decades, substantial progress has been made in understanding the role of integrated social-ecological systems (Colding and Barthel, 2019) and particularly the importance of the active participation of residents, knowledge, and expectations (Carpenter et al., 2012; Bąkowska-Waldmann, 2023). Also, one of the innovative solutions in the management of groundwater resources is to examine the systems of groundwater resources from a social-ecological system perspective (Giest and Howlett, 2014; Seward and Xu, 2019; Gain et al., 2021; Huggins et al., 2023). In the field of social-ecological systems, there is currently no universally agreed-upon framework or methodology. However, it typically encompasses a collection of interconnected social and environmental subsystems with interacting factors that mutually affect one another (Colding and Barthel, 2019; Tsuyuguchi et al., 2020). Furthermore, work on commons governance (a key sub-field of social-ecological systems research) has suggested that understanding the behavior of people facing collective action problems in the use of common-pool resources is essential. This includes the dynamics that emerge from collective action processes to govern the commons, which requires knowledge of the social and ecological factors that influence behaviors, intentions, and the institutional development that emerge from individual and collective decision-making (Andersson et al., 2021; Ghorbani and Bravo, 2016; Ostrom, 1990; Partelow et al., 2022).

Various frameworks have been proposed to examine the complexity and sustainability of social-ecological systems. Arguably the most widely used and cited framework is the Social-Ecological System Framework (SESF), originally developed by Elinor Ostrom (Ostrom, 2009; McGinnis and Ostrom, 2014). The framework's applications and associated methodologies have been reviewed in the recent literature (Thiel et al., 2015; Partelow, 2018; Nagel and Partelow, 2022). As shown in Fig. 1, the SESF framework consists of two primary conceptual layers. The decomposable multi-level framework has 8 variables or first-level subsystems with defined but general interactions between them. Six of the variables are considered internal to the system boundaries, including Resource System (RS), Resource Units (RU), Governance system (GS), Actors (A), Interactions (I), and Outcomes (O). The remaining two variables are considered external to the system boundaries: Social, economic, and political settings (S) and related ecosystems (ECO). Within each of the 8 first-tier variables are second-tier variables, 52 in total, which are more specific and can be defined and measured in the case studies. The SESF has been widely used as a diagnostic tool to identify factors involved in sustainable resource management, comprised of variables extracted from a wide variety of case studies on human-environment interactions (Nagendra and Ostrom, 2014; Basurto et al., 2013; Partelow, 2015, 2018; Thiel et al., 2015; Villamayor-Tomas et al., 2020). However, to our knowledge, few have explicitly focused on using the framework to guide indicator review and selection with the intended purpose of analyzing stakeholder preferences and perceptions of their role in local water governance sustainability (Partelow et al., 2021).

The SESF provides an important tool for examining groundwater sustainability issues, as the framework's history of development is explicitly rooted in common-pool resource management (Partelow, 2018). Common-pool resources are defined by their competition for use (rivalry/extractability), meaning two fishers can't share the use of a fish, or two farmers a unit of water; and further defined by their difficulties in excluding people from using the resource. Groundwater typifies a common-pool resource, because water is finite, and cannot be used by two people at the same time. It is further difficult to exclude people from pulling water out of the aquifer or to know how much they use, or how much water is left. Common pool resource problems typically require some form of collective action or cooperation among users to ensure sustainability to mitigate overexploitation. Understanding how different stakeholders involved in using or managing water resources perceive what is important for achieving sustainable solutions (e.g., indicators) is a critical step for finding inclusive governance paths forward and identifying potential gaps.

Groundwater systems are also social-ecological systems, meaning that changes to either social or biophysical features of the system have repercussive effects on the system as a whole. For example, if a drought occurs, it may lead to scarcity of water that lowers farming yields and income, influencing political decisions over water allocation rights and monitoring. Prior studies in Western Asia on groundwater governance have explored such social-ecological dynamics. Vener (2007), in interviews with 30 water management experts in the Kuras-Araks Basin, showed that the major obstacles to cooperation on integrated water resources management in this basin are political instability, administrative and structural issues, and the continued ethnic conflicts that have led to mistrust. Fereshtehpour et al. (2016) examined operator exploitation laws, highlighting that laws should be defined in such a way that takes into account ecosystem dynamics and the constraints that govern them to resolve disputes between operators and to motivate collective action. Furthermore, Molden et al. (2013) argue that water governance relates to the range of political, social, economic, and administrative systems that are in place to develop and manage water resources and deliver water services at various levels. Beyond Asia, Madani and Lund (2012) have shown that competition and confrontation over water rights allocations make cooperative solutions difficult, suggesting the need for a senior governing body to intervene and encourage collaborative solutions.

Given that the Hamedan-Bahar plain holds significant importance in western Iran and has encountered severe drought and water scarcity in recent times. Considering that most of the studies conducted in this area have measured the amount of groundwater and have not considered the ecological and economic dimensions. So, in this study, using the Socio-Ecological Systems Framework (SESF), various dimensions affecting the sustainability of groundwater sources have been investigated and identified. Therefore, this article is evaluated using the data of 22 experts in groundwater management and governance in the Hamedan-Bahar Plain using the Socio-Ecological Systems Framework (SESF). We examined 52 sustainability indicators of the social-ecological framework (SESF) through the application of the Ostrom framework.

We examine the following research objectives, guided by the literature, local contextual knowledge, and the SESF:

(1) Examine the social and ecological aspects, and their interactions, of the groundwater resource system on the Hamedan Bahar plain;
(2) Identify key variables influencing sustainability of water resources based on stakeholder inputs;
(3) Organize and analyze groundwater sustainability indicators with social-ecological system framework (SESF) to reveal current emphases and gaps;

(4) The social-ecological systems framework can simplify organizing diverse data for managers.

3. Materials and methods

3.1. Study area

The Hamedan-Bahar Plain, also known as Simineh River, is one of the four plains of the Hamedan region of Iran with an area of 2459 km^2, on the northern part of Alvand Heights (Fig. 2). The plain's area is 880 km^2 and the extent of the main aquifer is 468 km^2, with an elevation of 1579 km^2. This aquifer is recharged directly from precipitation, and surface currents, returns flow from agricultural, drinking, and industrial uses as well as underground inputs, and is discharged through groundwater extraction for various uses as well as underground output. Based on current groundwater data over the past years, there is a descending trend with continuous decline and reduction of groundwater reservoirs. There is no permanent river in the study area, and due to low average precipitation and its unpredictable temporal distribution, surface water plays a trivial role in the water supply of the agricultural sector. Thus, groundwater resources are the main source of more than 80 % of agricultural water. The increased cultivation, reduced precipitation, overexploitation, and inadequate nutrition of the aquifer in recent years have caused the groundwater level in this plain

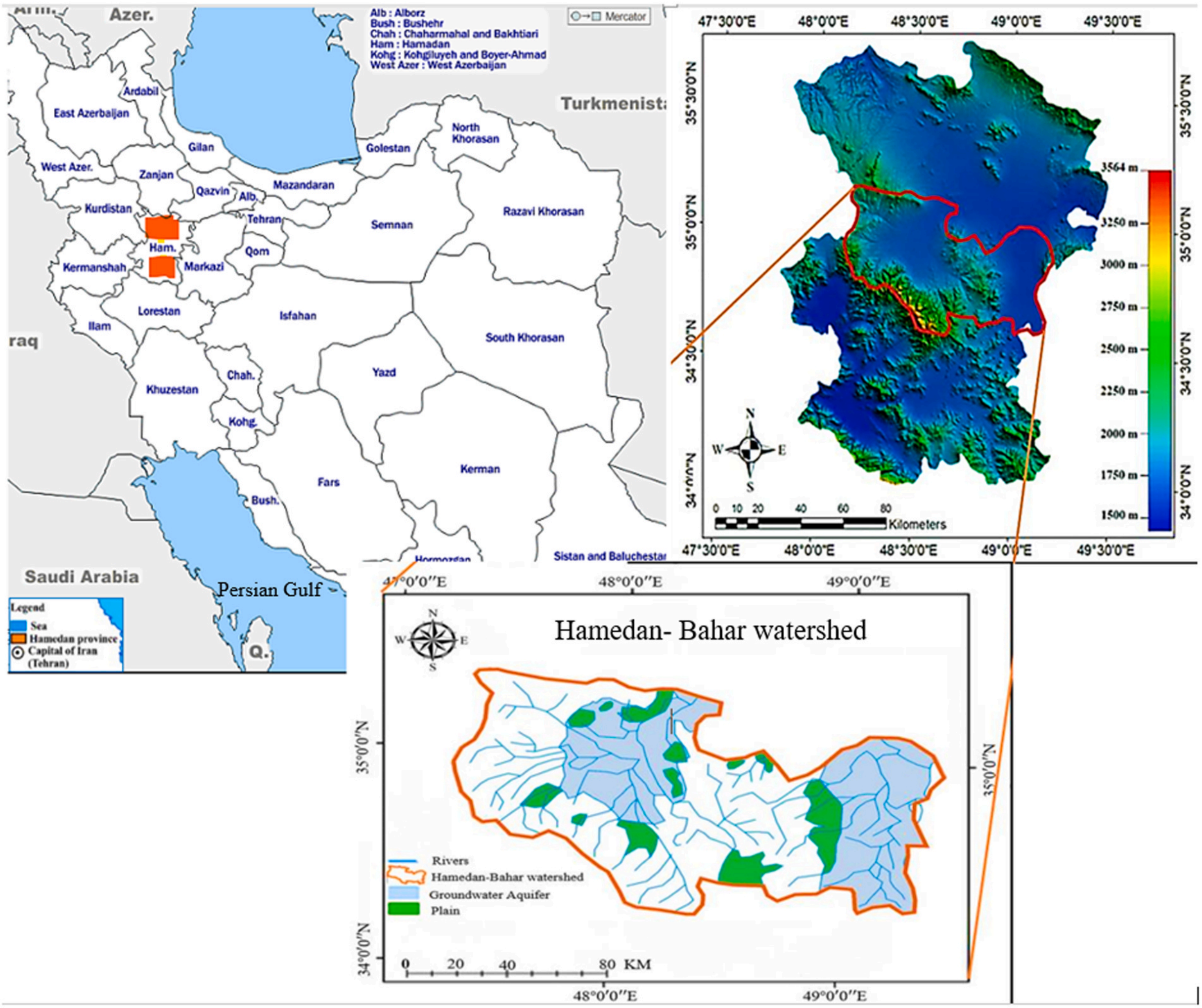

Fig. 2. . A general view of the study area in the Hamedan-Bahar Watershed, Iran (Sarami-Foroushani et al., 2023)

to decrease sharply and encounter a serious risk of destruction and surface subsidence. During this period, the local policy-makers have attempted to control the severe depletion of groundwater, although their efforts have failed due to continued illegal overexploitation causing a drop of more than 11 m in the aquifer level over the past two decades. The water crisis in the region has consequences for migration, unemployment, and environmental problems such as landslides, which have become serious threats to farmers, officials, and local stakeholders.

Overall, climatic conditions and water resources in Iran set the conditions for severe limitation of water resources, leaving more than two-thirds of the country in arid, semi-arid, and desert areas (Arjmand et al., 2020; Hosseini et al., 2019). As noted above, national groundwater resources have reached a critical condition due to overexploitation, the increasing numbers of illegal wells, and consecutive droughts (Mazaheri et al., 2021). Management trends over the last two decades have neglected issues such as increasing demand, intrinsic values of water, comprehensive studies, rights allocation issues, and public participation. However, the lack of adequate interaction with the private sector has also played a role. Currently, government agencies are supportive of measures to move away from the "past conditions" to the "ideal conditions" (Omranian Khorasani, 2015).

3.2. indicator selection

We conducted a review of the literature applying the SESF, in tangent with consultations with local experts 22 in the study region, to collect sets of contextually relevant indicators for groundwater sustainability. Many studies applying the SESF need to develop indicators to empirically measure the first- and second-tier variables of the framework, and thus there is substantial guidance in the literature for study design. The review by Partelow (2018) additionally provides a list of all the indicators used in the published SESF literature, which provides further inputs. In addition, the author's local knowledge informed the final selection of indicators specific to groundwater governance. Throughout this process, we categorized the indicators into the relevant first-tier variables of the SESF to structure the social-ecological framing of the study. Furthermore, beyond direct indicator selection, support for the relevance of each first-tier variable is provided from the broader social-ecological systems and water literature: Social, Economic, and Political Settings (S) (Knüppe and Meissner, 2016; Orach and Schlüter, 2016), Resource Units (RU) (Vogt et al., 2015; Bluemling et al., 2021), Resource Systems (RS) (Ostrom, 1990; del Mar Delgado-Serrano and Ramos, 2015; Zogheib et al., 2018), Governance Systems (GS) (McGinnis and Ostrom, 2014), Actors (A) (Cole et al., 2014; Palomo and Hernández-Flores, 2019), Interactions (I) (Villamayor-Tomas et al., 2020) and Outcomes (Thiel et al., 2015; Barnett et al., 2020; Robertson, 2021). We did not include the External Ecosystems (ECO) variable due to the large geographic scope considered already internal to the case system.Table 1

3.3. Survey design and implementation

The primary purpose of the study is to gain insights into the local stakeholder knowledge about the status of the sustainability indicators above. In other words, which indicators do key informant stakeholders believe are stable or unstable in relation to groundwater management, and thus shaping sustainability outcomes? (Fig. 3). Rather than collecting observational data on all 52 indicators, we conducted a stakeholder survey with 22 locally informed expert key informants who are affiliated with the two important agricultural and water management organizations. We asked each to indicate, to their knowledge, the status of the indicator in relation to current groundwater management. Each key informant is involved in either the Agriculture Organization or the Regional Water Organization of Hamedan-Bahar. For each indicator, an 11-point Likert scale was provided. Collecting local expert knowledge

Table 1
Indicators are used to measure the first-tier variables. Each indicator is labeled with a number (#) for reference throughout the study.

SESF first-tier variables	Indicators
Social, Economic, and Political Settings (S)	Employment in agriculture (1), Rural per capita income (2), Income distribution (Gini coefficient)(3), Diversity of products in the region (4), Market access (5), Integration of agricultural lands (6), Farmer demand for groundwater resources (7), Population growth rate in the region (8), Farmer population density in the region (9), Age structure (10), Gender structure (11), Migration rate (12), Rural literacy rate (13), number of media (14), Number of media and educational programs in the field of water resources (15), Government policies in the field of water resources (16), Disputes and conflicts in the field of water resources (17), Installation of smart water meters (18), New irrigation equipment such as pressurized irrigation (19)
Resource Units (RU)	Rainfall (20), Potential of renewable groundwater resources (21), Economic value of groundwater in the region (22);
Resource Systems (RS)	The volume of renewable water (23), Specify hydrological boundary (24), Efficiency of transmission systems and water consumption (25), Balance between agriculture and environment (26), Watershed management projects (27)
Governance Systems (GS)	Number of governmental organizations in the field of water (28), Number of non-governmental organizations in the field of water (29), Communication and interaction of organizations in the field of water (30), Number of unauthorized wells (31), Number of smart meters (32), Electrification of water wells (33), Number of local water markets (34), Number of regulatory factors on groundwater abstraction control (35)
Actors (A)	Number of farmers operating in the region (36), Number of economic sectors consuming water (37), Number of social organizations operating (38), Amount of indigenous and local knowledge (39), Amount of social capital (trust, empathy, and participation) of farmers (40)
Interactions (I)	The amount of information exchange between farmers (41), Farmer interaction with each other in the field of water (42), Agreements and internal regulations between farmers (43), Interaction between economic sectors (44)
Outcomes (O)	Efficiency of groundwater resources in agriculture (45), Groundwater pollution (46), Groundwater abstraction volume (47), Groundwater reservoir deficit (48), Land subsidence rate (49), Number of floods (50), Extent of agricultural empowerment programs (51), Responsibility in water resources consumption (52)

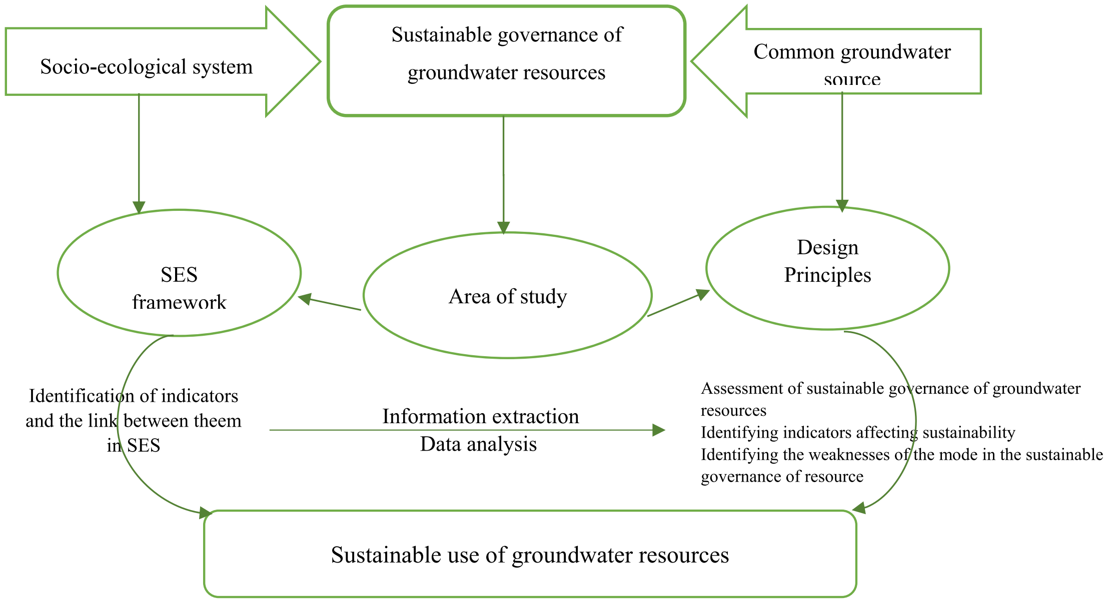

Fig. 3. Summary of the research approach and steps for this study.

enables drawing on local expertise while co-producing knowledge through an inclusive methodology. The survey was constructed and distributed in Persian. A translated sample of the survey is provided in English for reference (Appendix Table S1). The Likert rating of each indicator provided a standardized response format for statistical analysis and allowed us to identify which indicators within the 7 SESF first-tier variables are perhaps most influential, stable, or lacking attention in current water governance practices.

3.4. Data analysis

3.4.1. Description of measured indicators

As mentioned, Hamadan-Bahar plain is one of the important agricultural plains in the west of Iran, which has an important contribution to agricultural production, considering that groundwater plays an important role in the agricultural production of the region, to measure the sustainability of groundwater resources from the framework Ostrom was used. Based on the information collected from the Agricultural Jihad Organization of Hamedan Province, the per capita income index in the agricultural sector is 27 % and the employment rate in the agricultural sector is 46 %. In terms of population indicators, 36.7 % are rural residents, and the annual population growth rate is 3 % on average. In terms of population density in rural areas, it is 33 people per square kilometer, and the migration rate is 66.3 %, and the literacy rate is 89.1 %. According to the interviews with the organization's experts, there are 2–3 cases of disputes and disputes between farmers in the field of water. In the use of technology, 31 % of wells in the agricultural sector are equipped with smart meters. In terms of rainfall, it is 6388 million cubic meters annually, of which 2907 million cubic meters are renewable water (Renewable water is the amount of water that the basin can recover during the annual water cycle). So far, 4 artificial feeding projects have been implemented to restore groundwater resources in this plain. Also, due to the decrease in rainfall and recent droughts, the number of unauthorized wells has increased to 807 in this plain, and 6 teams of patrols and patrols have been activated in this plain to prevent and seal unauthorized wells. In the actor sector, which means farmers using groundwater resources, 23,291 people are members of water-collecting cooperatives, and the amount of social capital (interaction and empathy) is 36.8 %. In the governance system sector, there are 13 government organizations, 6 civil organizations, and 5 private sector organizations working in the field of water resources.

The meaning of hydrological demarcation of the watershed is the area where all the runoff caused by the rainfall falling on it is received by a river a waterway a lake or a water source. Accurate identification of the watershed boundary is a fundamental thing in the evaluation of the hydrological model. The demarcation between the basins is the basis of hydrological analysis, and the border of the separated plains based on the demarcation of the Ministry of Energy was prepared by the regional water joint-stock company of Hamadan province (Ministry of Energy, 2002).

3.4.2. Methods of measuring indicators

There are popular techniques to measure multi-criteria decision-making, including the TOPSIS, AHP, and SAW methods, further explained below. All these methods are part of multi-criteria decision-making methods that rank the number of options based on some criteria. The Analysis Hierarchy Process (AHP) was first proposed by Thomas El Saaty in 1980 (Saaty, 1995). In AHP, the evaluation is done in the form of pairwise comparisons, and based on the hourly standard table, numerical scoring is assigned to them (Hwang and Yoon, 1995). SAW method, The weighted simple sum model (SAW) is one of the simple methods of multi-indicator decision-making, so that by calculating the weights of the indicators, the most suitable option can be calculated. The Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS) is based on calculating the distance between the alternatives from the positive ideal solution (PIS) and negative ideal solution (NIS). This model was proposed by Huang and Yoon in 1981 and is often used as a rigorous multi-criteria decision model. It should have the minimum distance from the PIS (best possible condition) and the maximum distance from the NIS (worst possible condition). The Shannon's entropy method was used to weigh the indicator importance and the TOPSIS software was used to rank them.

Multi-criteria decision-making methods can be used to assess sustainability by ranking the factors affecting a system. Collecting a full data set on all system factors to be considered is important (i.e., economic, social, and ecological dimensions) to ultimately provide a comprehensive calculation for sustainability assessment (Hosseini et al., 2019). In multi-criteria decision-making problems, especially multi-indicator decision-making problems, having and knowing the relative weights of the available indicators is an effective step in the problem-solving process and is necessary.

Shannon's (1948) entropy theory, later put forward by Li (2010), enables the weighting calculations of indicators when conducting a TOPSIS analysis, weighting the relative importance of each indicator comparatively (Asgharpour, 2021). This is done with a decision matrix, where *m* options are evaluated based on *n* criteria, weighted using the concept of entropy. If we denote the decision matrix by X and each of its roots by xij, first the decision matrix must be normalized. The normalized matrix is denoted by N and each row is denoted by nij (Hakimi et al., 2017). In the Shannon entropy technique, according to the weights obtained from the indicators in this step, indicators that have more relative dispersion, are more important and their influence is greater in choosing the optimal option (Jun et al., 2013).

Conducting the full analysis of the data, TOPSIS with Shannon entropy weighting, includes the following steps (Asgharpour, 2021). In the first step, the decision matrix of raw survey data (rows of survey inputs and columns of governance indicators) was described (Appendix Figure S1). In the second step, the "weighted scaleless" matrix was created using the formula: $V = N_{D.} \times W_{m*n}$ where (v) is a weighted scaleless matrix, (N_D) is the value of each index is unweighted, and (W_{m*n}) is a weight vector. In the next step, the positive ideal (A^+) and negative ideal (A^-) alternatives were determined using the following formula: Positive ideal alternative $=A^+ = \{(\max V_{ij} | j \in j), (\min V_{ij} | J \in j`) | i=1,2,\ldots m\} = \{V_1^+, V_2^{\ +}, \ldots, V^+ i, \ldots, V_n^+\}$; Negative ideal alternative $=A^- = \{(\min Vij | j \in j), (\max Vi\ j | J \in j`) | i=1,\ldots,m\}$ $= \{V1, V2, \ldots Vn\}$; $j` = \{j=1, 2 \ldots n, |$ js relating to the cost$\}$; $J=\{j=1,2,\ldots,n|$ js relating to the profit$\}$.

In the fourth step, the distance was calculated using the Euclidean method as follows. The i-th alternative's distance from the PIS:

$$d_{i+} = \left\{ \sum_{j=1}^{n} \left(V_{ij} - V_j^+ \right)^2 \right\}^{0.5}, i = 1, 2, 3, \ldots, m$$

The i-th alternative's distance from the NIS:

$$d_{i-} = \left\{ \sum_{j=1}^{n} \left(V_{ij} - V_j^- \right)^2 \right\}^{0.5}, i = 1, 2, 3, \ldots, m$$

In the fifth step, the ratio of the relative proximity of A_1 was calculated using the following formula:

$$cli = \frac{d_1^-}{d_1^- + d_1^+} 0 \le cli \le 1 \quad i = 1, 2 \ldots m$$

Table 2
The 10 weighted negative (top) and positive (bottom) indicators.

Indicator	SESF	Weighted value
Illegal wells (35)	Gov	0.066 (-)
Abstraction volume of groundwater (47)	Outcome	0.058(-)
Disputes and conflicts in the field of water resources (17)	Soc, Eco, Pol	0.337(-)
Groundwater reservoir deficit (48)	Outcome	0.052(-)
Employment in the agricultural sector (1)	Soc, Eco, Pol	0.048(-)
Land subsidence (49)	Outcome	0.047(-)
Farmer demand for groundwater resources (7)	Soc, Eco, Pol	0.045(-)
empathy and participation) of farmers (40)	Actors	0.044(-)
Farmer population density in the region (9)	Soc, Eco, Pol	0.04(-)
Number of floods (50)	Outcome	0.038(-)
Groundwater pollution (46)	Outcome	0.037(-)
↑ **Negative – Positive** ↓ (see Table SX for all values)		
Number of smart meters (32)	Gov	0.017(+)
Number of social organizations operating (38)	Actors	0.018(+)
Number of media and educational programs for water resources (15)	Soc, Eco, Pol	0.018(+)
Rural literacy rate (13)	Soc, Eco, Pol	0.019(+)
Gender structure (11)	Soc, Eco, Pol	0.019(+)
Electrification of water wells (33)	Gov	0.02(+)
Market access (5)	Soc, Eco, Pol	0.02(+)
The amount of information exchange between farmers (41)	Interactions	0.023(+)
Population growth rate in the region (8)	Soc, Eco, Pol	0.032(+)

Finally, in the sixth step, cli^{+}, based on the alternative's values, all were ranked and ordered.

In order to examine, compare, and visually plot the relative importance of sustainability of the aggregate indicator scores in each of the first-tier variables of the SESF, the different resulting quantities were converted to relative scaleless data. To do this, the minimum and maximum values of each indicator were determined and the range of changes was obtained (rounded to the nearest 10th (i.e., 0.1)). The minimum value was then subtracted from the numerical value of each indicator and divided by the range of the fluctuations to obtain relative scaleless data between zero and one. The ranks zero to 0.2 were considered highly unsustainable; 0.2–0.4 unsustainable; 0.4–0.6 semi-sustainable; 0.6–0.8 sustainable, and 0.8–1 highly sustainable. A radar plot was used for comparative visualization (Cecilia Wong, 2006).

4. Findings

4.1. TOPSIS weighting of indicators

The criteria were weighted in TOPSIS software using Shannon's entropy technique and the following steps were taken. Formation of the decision matrix; the decision matrix contains information and entropy can be used as a criterion for its evaluation. Here, the decision matrix is the final score obtained from the average score of the questionnaires. The weights of the indicators were obtained using Shannon's entropy method in TOPSIS software. The selected results of the top 10 negative and positive weighted indicators results are presented in Table 2, with a full table in Appendix Table S3. In this matrix, the profit index has a positive utility, while the cost index has negative utility. According to the results, the item "illegal wells" with negative utility (cost) had the highest weight (0.066) among other indicators, followed by indicators with codes (47, 48, 1, 49, 7, 40, 9, 50, 46, 17, and 8, respectively) which related to: abstraction volume of groundwater (0.058), groundwater reservoir deficit (0.052), employment in the agricultural sector (0.048), land subsidence (0.047), farmers' abstraction of groundwater resources (0.045), number of exploiting farmers (0.044), the population density of farmers in the region (0.04), flood (0.038), groundwater pollution (0.037), conflicts and disputes over water (0.036) and population growth rate in the region (0.032) with negative utility. They had the greatest impact on the unsustainability of groundwater resources in Hamedan-Bahar Plain (Table 2).

4.2. Positive (PIS) and negative (NIS) ideal states of each indicator with near-ideal alternative

The positive and negative ideal state calculations for each indicator were calculated (Appendix Table S4), which determine the distance of the i-th alternative from the ideal alternative (highest performance of each indicator) with the A^{+} sign and determining the distance of the i-th alternative of the minimum alternative (lowest performance of each indicator) with the A^{-} sign. Accordingly, the near-ideal alternative will have the minimum distance from the positive ideal state and the maximum distance from the NIS (Cavallaro, 2010). In the next step, the difference or distance of each item is calculated using the Euclidean method (Table 3). The "illegal wells" (35) and "abstraction volume of groundwater resources" (47), as a negative indicator (cost), had the greatest impact on the unsustainability of groundwater resources in the region, while land subsidence (49), reservoir deficit (48) and groundwater pollution (46) are the next most influential indicators, respectively (Table 3).

Determining the near-ideal alternative involved taking two steps (Table 3). First, the relative proximity of A_1 was calculated using the formula between zero and one, with the number one indicating the highest rank and the number zero indicating the lowest rank in the set (Izadi et al., 2010). Next, the alternatives were ranked in ascending to descending order. The results of applying the weights and calculating the proximity of the alternatives to the ideal solution are presented in Table 3. According to the alternative of the nearest-ideal solution, the results of ranking the indicators show that monitoring agents (#35), watershed management projects (#27), transmission efficiency, and water consumption (#25) have the greatest influence on the sustainability of groundwater resources in Hamedan-Bahar Plain. In contrast, the number of illegal wells, land subsidence, and abstraction volume of groundwater have the most negative influence on groundwater resources in the region.

4.3. Comparing social and ecological sustainability with the SESF

Prescott-Allen (1996) provides a basic assessment tool for sustainability that provides a simple systematic way of measuring and combining indicators to conclude the status of social-ecological interactions. We base our aggregate indicator scores and weighting on this basic premise, dividing sustainability assessment into five levels. The weight of all indicators within each first-tier variable was averaged to get the total near-ideal alternative. The ranks zero to 0.2 were considered highly unsustainable; 0.2–0.4 unsustainable; 0.4–0.6 semi-sustainable; 0.6–0.8 sustainable, and 0.8–1 highly sustainable.

The Resource System (RS) and Resource Unit (RU) indicators have the most positive influence on sustainability based on the average weighting of indicator values from the near-ideal alternative calculations (Table 4). In contrast, the Governance System (GS), Actor (A), and Interaction (I) first-tier variables were evaluated as negatively influencing sustainability under the Prescott-Allen classification, along with Outcomes (O) being the lowest. The results are plotted for visual comparative reference in Fig. 4. The RS indicators, with an average weight of 0.74, are from this analysis in a sustainable condition, with the key indicators being watershed management projects and the efficiency of water transmission and consumption systems. The second rank goes to the RU indicators with an average weight of 0.7, with the key indicators being the precipitation rate and potential of renewable groundwater resources.

The third rank goes to the Interactions indicators with an average weight of 0.6, with key indicators measuring the rate of information exchange between farmers, farmers' interaction about water, farmer agreement, and internal regulations among farmers.

Table 3
Ranking of indicators affecting the sustainability of groundwater resources, calculated, ranked, and ordered by the indicators with the least distance from the positive ideal solution (i.e., #35) and the greatest distance from the negative ideal solution (i.e., #39). Indicator ranked 1, is interpreted as having the most positive relative influence on sustainability, while the lowest-ranked indicator is interpreted as having the most negative influence. Indicator names are shortened for brevity, but each retains the same reference number throughout the paper for identification. Proximity coefficient to ideal = PCI.

Rank	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Indicators	Regulatory factors (#35)	Watershed management projects (#27)	Efficiency and consumption. (#25)	Hydrological boundaries (#24)	Number of farmers (#36)	Rainfall (#20)	The balance between agri. and env. (#26)	The volume of renewable water (#23)	The number of media and education prog. (#15)	The potential of renewable groundwater (#21)	Government policies (#16)
PCI	0.812	0.807	0.802	0.779	0.771	0.766	0.761	0.758	0.753	0.752	0.746
Rank	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
Indicators	Installation of smart water meters (#18)	Integration of agricultural lands (#6)	The economic value of groundwater (#22)	Number of media (#14)	Responsibility for water consumption (#52)	Agriculture groundwater efficiency (#45)	Number of governmental organizations (#28)	Number of NGOs in water (#29)	Rural literacy rate (#13)	Migration rate (#12)	Communication and interaction of orgs. (#30)
PCI	0.741	0.735	0.720	0.715	0.703	0.700	0.689	0.676	0.664	0.663	0.654
Rank	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**
Indicators	Number of regulatory factors (#35)	Extent of empowerment programs (#51)	Interaction of economic sectors (#44)	Number of sectors using water (#37)	New irrigation equipment (#19)	Number of local water markets (#34)	Regulations between farmers (#43)	Farmer interactions (#42)	Diversity of products (#4)	Income distribution (#3)	Rural per capita income (#2)
PCI	0.649	0.642	0.631	0/6	0.594	0.568	0.566	0.553	0.519	0.494	0.493
Rank	**34**	**35**	**36**	**37**	**38**	**39**	**40**	**41**	**42**	**43**	**44**
Indicators	Electrification of water wells (#33)	Number of smart meters (#32)	The number of social organs. operating (#38)	Gender structure (#11)	Age structure (#10)	Farmer groundwater demand (#7)	Integration of agricultural lands (#5)	Employment in agriculture (#1)	Disputes and conflicts (#17)	Farmers' population density (#9)	Information exchange among farmers (#41)
PCI	0.492	0.396	0.366	0.349	0.341	0.340	0.336	0.314	0.306	0.287	0.251
Rank	**45**	**46**	**47**	**48**	**49**	**50**	**51**	**52**			
Indicators	Population growth rate (#8)	Social capital of farmers (#40)	Groundwater deficit (#48)	Groundwater pollution (#46)	Number of floods (#50)	Groundwater use volume (#47)	Land subsidence (#49)	Number of illegal wells (#39)			
PCI	0.210	0.210	2197	192	0.184	0.155	0.113	0.088			

Table 4
Weighting and ranking of the SESF first-tier variables when the indicators within each are averaged. The higher rank is interpreted as having an average indicator score that more positively influences sustainability outcomes. The following sustainability influences were based on the following: 0.0–0.2 (highly unsustainable); 0.2–0.4 (unsustainable); 0.4–0.6 (semi-sustainable); 0.6–0.8 (sustainable), and 0.8–1 (highly sustainable).

Indicators	Resources system	Resources Unit	Interactions	Governance System	Socio-ecological Settings	Actor	Outcomes
Rank	1	2	3	4	5	6	7
Number of indicators	5	3	4	8	19	5	8
Average weight	0.74	0.7	0.6	0.46	0.45	0.4	0.31
Max.	0.8	0.7	0.6	0.8	0.7	0.6	0.7
Min.	0.7	0.7	0.6	0.3	0.2	0.2	0.2

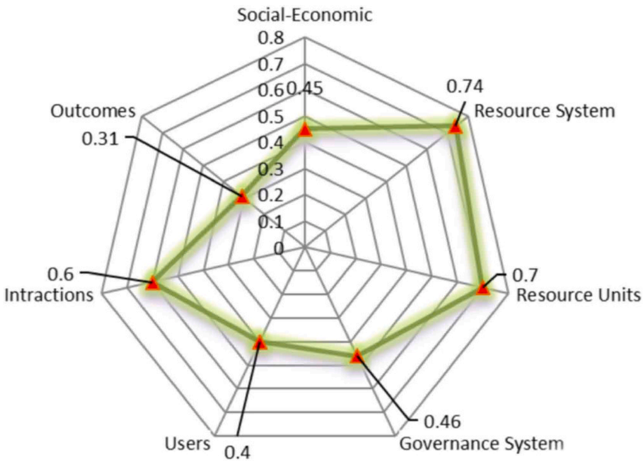

Fig. 4. Radar plot of the average indicator values for each SESF first-tier variable.

The GS indicators, measuring the number of smart meters, electrification of water wells, and number of monitoring agents to control groundwater abstraction, are semi-sustainable with an average weight of 0.46. The Soc, Eco, Pol., indicators with an average weight of 0.45, semi-sustainable, with indicators being literacy of rural people, number of media and educational programs on water resources, government policies regarding water resources, and disputes and conflicts over water resources. The Actor indicators have an average weight of 0.4, including a number of operating social organizations, level of indigenous and local knowledge, and amount of social capital. The Outcome indicators have to lowest rank, with an average weight of 0.31. The main indicators are the efficiency of groundwater resources in agriculture, the extent of farmers' empowerment programs, and responsibility for water consumption. Overall, this analysis suggests that there are both positive and negatively influential indicators of concern for, and potentially shaping overall sustainability, but that social factors more generally rank lower, suggesting they are of more concern for sustainability. A full table of each indicator values within each SESF first-tier variable is shown in Appendix Table S5.

5. Discussion

Access to new information on groundwater resources provides an opportunity to analyze the sustainability and governance of this resource. This study used Ostrom's SESF to examine the status of various dimensions of social, economic, and environmental sustainability. It also showed how the absence or achievement of some of Ostrom's principles might have contributed to the unsustainability of the Hamedan-Bahar Plain. This study used one of the multi-criteria decision-making methods, namely the TOPSIS method in combination with Shannon's entropy method to evaluate and rank the sustainability of groundwater resources of Hamedan-Bahar Plain using Ostrom's SESF. To this aim, first the alternatives and criteria were determined and then questionnaires were presented to a panel of experts to evaluate the criteria and alternatives. The experts' views were collected and Shannon's entropy and TOPSIS methods were used to identify and rank the criteria and alternatives influencing the sustainability of groundwater resources in Hamedan-Bahar Plain.

The results and findings of the research show that from the experts' point of view, the RS and RU criteria had the highest score in groundwater sustainability, while the I, GS, and S were in semi-sustainable positions. As shown in the findings section, the RS criterion, with the indicators of "watershed management projects, artificial recharge, and water storage pools" has the greatest effect on the sustainability of groundwater resources in the region. As we know, a decrease in the discharge of wells, springs, and aqueducts in the plains will disturb the water equilibrium and consequently remove the environmental balance of watersheds, resulting in excessive unsustainability of groundwater resources. Artificial recharge of aquifers, like the flood spreading method in the plains, is one of the strategies that can be used for the sustainability of water resources. By infiltrating the flood into the aquifer, this method increases the reservoir volume and prevents the severe decline of groundwater level. It also reduces flood damage, increases the volume of groundwater aquifers, and plays an important role in the rehabilitation of degraded pastures and desertification. Balancing the condition of aquifers, it will prevent the land subsidence phenomenon. Moreover, using the capacity of the ground reservoir to store excess water in the cropping season will be another advantage of this method. The above findings in our study align with numerous other studies including those by Yang et al. (2019), Malmir et al. (2022), Cai et al. (2018), Ali et al. (2017), Noori et al. (2023), Medema et al. (2016), Reddy et al. (2017), Floress et al. (2015).

Another sub-criterion of RS is "efficiency of water transmission systems". Water transmission is important in agriculture because the highest amount of water consumption in groundwater aquifers occurs in the agricultural sector. In the case of using water transmission methods such as canals and pipes with Polyethylene fittings in the water supply and irrigation system, it is possible to prevent water loss during transmission. On the other hand, in addition to completing the process of water transmission in agriculture, it will save water consumption, help maintain water reserves, prevent water pollution, increase productivity and yield, and ultimately lead to self-sufficiency. The efficiency of water transmission systems in this study is consistet with those findings in Sun et al. (2016), Cai et al. (2018), Brown et al. (2015), Kotir et al. (2016), Fang and Chen (2017).

The "Precipitation and renewability of groundwater resources", a sub-criterion of the RU recharging groundwater aquifers, is considered the renewable water potential of the province. The last decade's low precipitation on the one hand and the farmers' excessive discharge on the other hand has put Hamedan-Bahar Plain in an precarious condition. Therefore, considering the role of precipitation in the renewal of groundwater resources, careful and appropriate plans should be developed for farmers and their crops according to their water needs based on the precipitation rate. Findings of this section align with those of Sulaiman et al. (2019), Ahmad and Al-Ghouti, (2020), Wei et al. (2017), Luo et al. (2020), Hussain et al. (2019), Jiang et al. (2017), Xie et al. (2018), Bierkens and Wada, (2019).

The "Economic value of water" is another factor in the RU criterion. Determining the economic value of water input in the agricultural sector is an important tool for water management and the development of applied policies in this regard. The economic value of water in the agricultural sector is a political tool to increase water efficiency, reduce water demand, manage the irrigation systems, and return the costs. The results of this section are compatible with the findings of Pires et al. (2017), Brown et al. (2015), Distefano and Kelly (2017) and Hering et al. (2015).

In the I criterion, the sub-criterion of "Farmers' agreement and interaction on water issues and agreement on collective laws" is another factor influencing the sustainability and proper use of groundwater resources. It is one of the important and influential factors in the sustainability of CPR, especially in the area of groundwater resources. Consensus in collective law with the findings from Yu et al. (2016), Meinzen-Dick et al. (2018), Rey et al. (2019), Sanchis-Ibor et al. (2017) and Westerink et al. (2017) are aligned with these indicator interpretations in our study.

In the GS criterion, based on the sub-criterion of "the existence of monitoring agents such as patrol teams to control water abstraction", the relevant organizations make regular and periodic inspections of wells, control the amount of water supply and operation, and punish those who violate the laws. The "existence of smart meters and electrification of wells" is another sub-criterion of the GS criterion. By installing meters and having agents read them, they become aware of the amount of groundwater abstraction which may help prevent over-abstraction. Also, by electrifying the wells and installing volume meters, they control the amount of water consumption and help preserve the environment, and reduce the costs of farmers by reducing the consumption of fossil fuels. Regulatory factors are one of the strategies to protect groundwater resources, also shown in the findings of Brendel et al. (2018), Megdal et al. (2015), Sun et al. (2016), Ashraf et al. (2017), Giri and Qiu (2016), Boretti and Rosa (2019), Singh and Bhakar (2021), Loucks and van Beek (2017).

In the S criterion, the sub-criterion of "media and educational programs on water resources" is effective in the sustainability of groundwater resources. Media are among the important elements in communication processes. If well selected, they can accelerate and facilitate communication. Mass media (including press, cinema, radio, television, computer games, the Internet, and social networks) are used. According to the results, the programs and training provided raise the public's awareness and increase the sustainability of the region's groundwater resources in the social setting sector. The Impact of Educational Programs and Media have also been demonstrated by Butler and Adamowski (2015), Sivapalan and Blöschl (2015), Arthington et al. (2018), Cominola et al. (2015).

Another influential factor in the S criterion is "policy-making about water". A major factor in the management of groundwater resources is the adoption of appropriate policies in this regard. The water management policy is aimed at water supply for the development of programs and policies on water and water resources in order to face the water crisis and compensate for the damage caused to the country's water resources. Political crises and policies regarding water resources may affect social relations and bring about local conflicts and tensions, protests, and other detrimental behaviors due to reasons such as increased water consumption, precipitation asymmetries in the country, population growth, unbalanced development, improper and excessive water consumption, especially stakeholder between farmers and industry. Therefore, it is very important to take this into account in order to preserve and sustain groundwater resources. Policy on groundwater resources has also been explored in similar ways in: Li and Qian 2018, Jia et al. (2019), Noori et al. (2023), Closas and Rap (2017), Li et al. (2018), Michael et al. (2017), Bhanja et al. (2017), Singh and Bhakar, (2021), Sarami Foroushani et al. (2021), Giordano et al. (2015), Safavi et al. (2015), Cai et al. (2018), Zomorodian et al. (2018), Arfanuzzaman and Rahman (2017), Chen et al. (2018), Kharrazi et al. (2016).

In the U dimension, social capital is one of the main reasons for the failure of development projects, the existence of individual and collective conflicts and tensions, lack of collective participation, high costs of social control, low social efficiency, and social disintegration (Woolcock, 2011). Therefore, social cohesion is considered an important factor affecting social capital and people's level of participation in development projects. In general, there is a close relationship between the three social components of trust, participation, and cohesion. This means that the greater the relationships between actors, the higher the level of trust between them and the more opportunities for collective action, cooperation, and participation among them; therefore, social capital and consequently cohesion will increase and participatory management will prove more successful and less costly (Pretty and Ward, 2001; Hahn et al., 2006). According to Ostrom's theory of collective action, in addition to government and private organizations, there are other actors in the form of local communities and non-governmental organizations who also manage and perform essential governance tasks. According to our findings, some of the factors are likely best managed, planned, and implemented by the government and private organizations, such as artificial recharge projects, balancing, increasing the efficiency of systems, etc., and some others are likely more effectively organized or self-organized and managed by farmers or actors, such as the exchange of information and interaction of farmers, internal agreements and the establishment of organizations relating. These findings build on other studies with similar insights such as by Westerink et al. (2020), Mirzaei et al. (2020), Yoder and Chowdhury (2018), Ruiu et al. (2017), Yaméogo et al. (2018), Dean et al. (2016), Miao et al. (2015), Leuenberger and Reed (2015), Tharmendra and Sivakumar (2016).

6. Conclusion

Due to droughts, floods, climate change, and water pollution, water resource governance has drawn the attention of researchers more than ever before. However, despite the role and importance of groundwater resources in human life and the environment, its challenges and problems have received little attention. In this study, we show how using novel mixed method approaches to apply Ostrom's social-ecological systems framework can substantially help to better understand the complexity of factors influencing the sustainability of groundwater resource management in Iran, which has received minimal attention. We show how a range of social, economic; governance and environmental indicators can have different influences on the system functions and outcomes. We base our evidence on local experts and stakeholders, which has provided locally relevant findings to inform where future management, research and governance efforts may be most effective in guiding policies and institutional development to guide groundwater systems towards more sustainable outcomes, that benefit and reduce harms and costs for both people and nature. Furthermore, the study demonstrates a new quantitative methodology for applying Ostrom's framework and provides novel contextual insights from Iran that enriches the potential for cross-case learning.

Therefore, by understanding the potential and importance of groundwater and its role in the sustainability of SESs, important measures can be taken towards this aim. On the other hand, it is necessary to evaluate sustainability to identify the weaknesses and achieve strong sustainability. The use of sustainability concepts is very important to the sustainability evaluation of an area, because these concepts reflect different types of sustainability and related issues. Inattention to poor sustainability will lead to unsustainable conditions in the region in the long run. Also, various social, economic, and environmental aspects should be considered in sustainability assessment.

Achieving sustainability in the groundwater resources of Hamadan-Bahar Plain requires the access of planners and decision-makers to new and reliable information in the field of agriculture and natural resources. As the results of the study showed, in order to maintain sustainability, the officials and planners should formulate plans for watershed projects of artificial feeding by directing excess water such as floods to groundwater sources.

On the other hand, the issue that has been considered in the management of groundwater resources is the efficiency of water transmission systems. Water transfer systems have a great effect in preventing the wastage of water resources. The use of advanced equipment and technologies in the transfer of water to fields plays an important role in the correct use and prevention of overharvesting of water resources and the correct direction of water to fields. An important issue that has attracted the attention of economists in recent years is the economic value of water resources, which is an important tool for water management and the development of practical policies in the agricultural sector. Finally, the level of agreement and interaction in water-related issues and agreement in collective laws among the farmers of the region is one of the important and influential human factors on groundwater resources. methods and plans and efforts toward the sustainability of natural resources will be fruitless. Therefore, according to Strom's theory, the existence of collective agreement in the use of common resources is one of the important and influential factors in the sustainability of common resources, especially in the field of groundwater resources. Hence, the integration of environmental, economic, and social benefits in a comprehensive manner is necessary to achieve the goals of resource sustainability governance. Creating balanced development between subsystems and balanced implementation of different policy intensities has a decisive effect on the development process of Strom's socio-ecological framework. Merely strengthening environmental protection policies while ignoring regional socio-economic development will not work and be effective. Therefore, achieving a positive interaction between socio-economic development and environmental protection requires finding a balance point. This requires emphasizing environmental protection during the process of economic development, interaction and participation of regional stakeholders, as well as achieving efficient use of resources through technological innovations and institutional reforms. It plays an important role in achieving the Sustainable Development Goals of the SESF.

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CRediT authorship contribution statement

Reza Movahedi: Writing – review & editing, Validation, Methodology, Investigation, Conceptualization. **Stefan Partelow:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Conceptualization. **Taraneh Sarami-Foroushani:**

Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Data curation, Conceptualization. **Hamid Ballali:** Writing – review & editing, Writing – original draft, Validation, Resources, Methodology, Investigation, Data curation, Conceptualization.

Declaration of Competing Interest

We declare there is no conflict of interest.

Data availability

Data will be made available on request.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2024.101889.

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