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# Preprint

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# Title

Using local knowledge to assess the sustainability of groundwater resources: applying the social-ecological systems framework to the Hamedan-Bahar Plain, Iran

# Authors

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# Abstract

Sustainable access to groundwater remains a key challenge for local users, managers and policy makers, particularly in arid agricultural regions such as Iran. Identifying and assessing the status of diverse sustainability indicators using local knowledge can act as a step in the right direction for often invisible and hard to measure resources, especially when developed through inclusive approaches that include expert stakeholder inputs. In this article, we apply Ostrom's social-ecological systems framework (SESF) to assess how the local knowledge of key informant stakeholders can be used to assess the sustainability of groundwater resources on the Hamadan-Bahar plain in Iran. We evaluate the importance of each of the SESF's first-tier variables based on 52 indicators attained from literature review and expert insights. Local knowledge is used to assess the sustainability status of each indicator through a survey of 22 key informants. For data analysis, we use the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and the Shannon Entropy methodologies to weight and rank indicators based on the data provided on their influence on sustainability. Findings suggest that the Resource System (RS) and Resource Unit (RU) indicators have the most positive influence on sustainability. 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.

**Key words:** Groundwater management, local knowledge, knowledge co-production, sustainability indicators, socio-ecological systems (SES), stakeholder inclusion, water governance, commons

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Key words: Local knowledge; knowledge co-production; Sustainability Indicators; socio-ecological systems (SES); water governance; commons

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# 35 **1.0 Introduction**

Sustaining groundwater resources is essential for human wellbeing, economic development and 36 37 environmental protection in many water scarce regions, particularly those dependent on local agriculture. 38 However, groundwater quality and quantity is often challenged by population growth, urban sprawl, 39 agricultural expansion and economic growth in recent decades (Yan et al., 2018; Ye et al., 2018; Xu et al., 40 2019; Liu et al., 2020). Groundwater remains a viable option because it is often cheaper, more convenient 41 and less vulnerable to pollution than surface water. Therefore, it is commonly used for public water supplies (Luker, 2017). The major difference between groundwater and surface water resources is that it 42 43 is very difficult to monitor and measure groundwater (Esteban, 2021). As a result, sustainable 44 groundwater use is more difficult due to uncertainties in the availability and stability of water over time, 45 exacerbating the collective action challenge of governance that often lacks a feedback mechanism on the 46 effectiveness of institutional development efforts (Asprilla-Echeverria, 2021).

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48 Today, more than half of the global urban population relies on groundwater to meet their basic needs 49 (Mishra et al., 2021), but many challenges remain for governance towards sustainability. As groundwater 50 use and dependence increase, the more challenges and problems will arise regarding the ownership, use, 51 access, protection and development of water resources, especially in border areas (Bogardi et al., 2021; 52 Eman and Meško, 2021; Katz, 2021). In many countries, water resources have been distributed without 53 clear use rights over space or time, creating challenges for human security and development when scarcity 54 arises (Bai et al., 2015; Feng et al., 2020). Governance aimed at ensuring sustainability needs to account 55 for such risks and uncertainties, and acknowledge the common-pool resource properties of water that 56 require collective action as well as forms of rights allocation (whether common property, state or private) 57 to ensure not only water access and use, but justice and equity in relation to who gets how much and 58 why.

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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, Di et al. (2022) show 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 multilevel 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) show how applying common-pool resource theory and the SESF can help unpack the factors shaping governance challenges in the large Rhine river watershed.

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73 In social-ecological systems such as groundwater, gathering data for comprehensive assessments remains 74 challenging. Developing and monitoring indicators to inform management options can be difficult, often 75 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. Elshall 76 et al., (2020) review the literature on management perspectives, sustainability indicators and typologies 77 78 for groundwater sustainability, noting that closing the science-policy gap will require: (i) engaged 79 stakeholders in participatory processes; (ii) improved understanding of social-ecological interactions and 80 scenarios; and (iii) acknowledges uncertainty in scientific knowledge and the diversity of societal 81 preferences in management. Furthermore, including stakeholders in water governance has been 82 recognized and outlined by the OECD, which suggest five principles for doing so (OECD, 2015). These principles include dimensions of mapping the relevant stakeholders and embedding their perspectives, 83 84 knowledge and participation in policy frameworks and decision-making processes. Doing so is argued as 85 critically important for broadening the knowledge base for decision making, meeting local needs, building trust and therefore higher compliance likelihood as well as increasing communication and transparency 86 87 in the associated processes (Reed, 2008; Schneider and Buser, 2017, Wehn et al., 2018). More broadly, stakeholder inclusion and the role of science in environmental governance has received substantial 88 89 attention over the last few decades (Bäckstrand, 2004; Reed, 2008; Newig and Fritsch, 2009).

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Harnessing local knowledge is increasingly utilized 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 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., 2017; Tengö et al., 2017; Norström et al., 2020).

In this article, we examine the status of 52 sustainability indicators based on local knowledge from 22 expert key informants on local groundwater management and governance on the Hamadan-Bahar plain in Iran using the Social-Ecological Systems Framework (SESF). Drawing on locally informed stakeholders to indicate the status of each indicator, we provide an empirical assessment of the social and ecological priorities placed on 52 groundwater sustainability indicators associated with 7 first-tier variables of the SESF. Below we briefly introduce the SESF, its use in previous studies and relevance for water governance and sustainability analysis before introducing the case study area and methods.

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# 107 **1.1 Understanding groundwater sustainability with the Social-Ecological Systems Framework** 108 (SESF)

109 Natural resource sustainability requires an understanding of the complexity of integrated systems (i.e., 110 social, biophysical, economic) and their interactions (Cumming et al., 2013). Historically, many natural resource management approaches have failed due to fragmented, isolated or limited disciplinary 111 112 perspectives shaping decision-making (Holling and Meffe, 1996; Holling, 2003; Bergstrom et al., 2021). However, over the last few decades, substantial progress has been made in understanding the role of 113 114 integrated social-ecological systems (Colding and Barthel, 2019) and particularly the importance of the 115 active participation of local residents, knowledge and expectations (Carpenter et al., 2012). Furthermore, 116 work on commons governance has suggested that understanding behavior of people facing collective 117 action problems in the use of common-pool resources, and the dynamics that emerge from collective action processes to govern the commons, requires knowledge of the social and ecological factors that 118 influence behaviors, intentions and the institutional development that emerge from individual and 119 collective decision-making (Ostrom, 1990; Ghorbani and Bravo, 2016; Andersson et al., 2021; Partelow et 120 121 al., 2022).

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Various frameworks have been proposed to examine the complexity and sustainability of social-ecological systems. Arguably the most widely used and cited frameworks 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). The framework is a decomposable multi-level framework with 8 first-level variables or sub-systems with defined but general interactions between them

(Figure 1). Six of the variables are considered internal to the system boundaries, including: Resource 129 System (RS), Resource units (RU), Governance system (GS), Actors (A), Interactions (I) and Outcomes (O). 130 131 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 132 variables, 52 in total, which are more specific and can be defined and measured as appreciate to the case 133 134 studies of interest. The SESF has been widely used as a diagnostic tool to identify factors involved in sustainable resources management in response to the challenges posed in over a hundred case studies 135 136 on human-environment interaction (Nagendra and Ostrom, 2014; Basurto et al., 2013; Thiel et al., 2015; Partelow, 2018; Villamayor-Tomas et al., 2020). However, to our knowledge, few have explicitly focused 137 on using the framework to guide indicator review and selection with the intended purpose to analyze 138 stakeholder preferences and perceptions of their role in local water governance sustainability (Partelow 139 et al., 2021). 140



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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). Ostrom first studied groundwater governance in Los Angeles during her doctoral studies in the 1950s (Ostrom 1965), later using case studies from fisheries, forestry and irrigation systems to refine theories of institutional change, collective action and rational choice theory in her study of the commons (Ostrom,

1990; Ostrom 1998). Common-pool resources are defined by their competition for use 150 151 (rivalry/extractability), meaning two fishers can't share the use of a fish, or two famers a unit of water; 152 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 153 is further difficult to exclude people from pulling water out of the aquifer, or to know how much they use 154 155 or how much water is left. Common-pool resource problems typically require some form of collective 156 action or cooperation among users to ensure sustainability to mitigate overexploitation. Understanding 157 how different stakeholders involved in using or managing water resources perceive what is important for 158 achieving sustainable solutions (e.g., indicators) is a critical step for finding inclusive governance paths 159 forward and identifying potential gaps.

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Groundwater systems are also social-ecological systems, meaning that changes to either social and 161 biophysical features of the system have repercussive effects on the system as whole. For example, if a 162 163 drought occurs, it may lead to scarcity of water that lowers farming yields and income, influencing political 164 decisions over water allocation rights and monitoring. Prior studies in western Asia on groundwater 165 governance have explored such social-ecological dynamics. Vener (2007), in interviews with 30 water 166 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 167 168 issues and the continued ethnic conflicts that have led to mistrust (Vener, 2007). Fereshtehpour et al., 169 (2016) examined operator exploitation laws, highlighting that laws should be defined in such a way that 170 takes into account ecosystem dynamics and the constraints that govern them to resolve the disputes 171 between operators and to motivate collective action. Furthermore, Molden et al., (2010) argue that water governance relates to the range of political, social, economic and administrative systems that are in place 172 to develop and manage water resources and deliver water services at various levels. Beyond Asia, Madani 173 174 and Lund (2012) have shown that competition and confrontation over water rights allocations make 175 cooperative solutions difficult, suggesting the need for a senior governing body to intervene and 176 encourage collaborative solutions.

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In this study, 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;

182 (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
- 185

(4) Reflect and discuss findings for future researchers and policymaking in the region

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# 187 **2.0 Methods**

#### 188 **2.1 Study Area**

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190 The Hamedan-Bahar Plain, also known as Siminehrood, is one of the four plains of the Hamedan region of 191 Iran with an area of 2459 km<sup>2</sup>, on the northern part of Alvand heights (Figure 2). The plain's area is 880 192 km<sup>2</sup> and the extent of the main aquifer is 468 km<sup>2</sup>, with an elevation of 1579 km<sup>2</sup>. This aquifer is recharged 193 directly from precipitation, surface currents, returns flow from agricultural, drinking and industrial uses 194 as well as underground inputs and is discharged through groundwater extraction for various uses as well 195 as underground output. Based on current groundwater data over the past years, there is a descending 196 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 197 198 water plays a trivial role in water supply of the agricultural sector. Thus, groundwater resources are the 199 main source for more than 80% of agricultural water. The increased cultivation, reduced precipitation, 200 overexploitation, and inadequate nutrition of the aquifer in recent years have caused the groundwater 201 level in this plain to decrease sharply and encounter the serious risk of destruction and surface subsidence. During this period, the local policy-makers have attempted to control the severe depletion of 202 203 groundwater, although their efforts have failed due to continued illegal overexploitation causing a drop 204 of more than 11 meters in the aquifer level over the past two decades. The water crisis in the region has 205 consequences for migration, unemployment and environmental problems such as landslides, which have become serious threats to farmers, concerning officials and local stakeholders. 206





Figure 2. Study area of Hamadan–Bahar watershed in Hamadan province, Iran.

210 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., 211 212 2020). As noted above, national groundwater resources have reached a critical condition due to overexploitation, the increasing numbers of illegal wells and consecutive droughts (Mazaheri and Manafi, 213 2017). Management trends over the last two decades have neglected issues such as increasing demand, 214 intrinsic values of water, comprehensive studies, rights allocation issues and public participation. 215 However, the lack of adequate interaction with the private sector has also played a role. Currently, 216 217 government agencies are supportive of measures to move away from the "past conditions" to the "ideal conditions" (Omranian Khorasani, 2015). 218

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# 221 **2.2 Literature review and indicator selection**

We conducted a review of the literature applying the SESF, in tangent with consultations with local experts 222 223 in the study region, to collect sets of contextually relevant indicators for groundwater sustainability. Many 224 studies applying the SESF need to develop indicators in order to empirically measure the first- and second-225 tier variables of the framework, and thus there is substantial guidance in the literature for study design. 226 The review by Partelow (2018) additionally provides a list of all the indicators used in the published SESF 227 literature, which provided further inputs. In addition, the authors local knowledge informed the final selection of indicators specific to groundwater governance. Throughout this process we categorized the 228 229 indicators into the relevant first-tier variables of the SESF to structure the social-ecological framing of the 230 study. Furthermore, beyond direct indicator selection, support for the relevance of each first-tier variable 231 is provided from the broader social-ecological systems and water literature: Social, Economic, and 232 Political Settings (S) (Knüppe and Meissner, 2016; Orach and Schlüter, 2016), Resource Units (RU) (Vogt 233 et al., 2015; Bluemling et al., 2021), Resource Systems (RS)(Ostrom, 1990; Del Mar Delgado-Serrano and 234 Ramos, 2015; Zogheib et al., 2018), Governance Systems (GS) (McGinnis and Ostrom, 2015), Actors (A) 235 (Cole et al., 2014; Palomo and Hernández-Flores, 2019), Interactions (I) (Villamayor-Tomas et al., 2020) 236 and Outcomes (Thiel et al., 2015; Barnett et al., 2020; Robertson, 2021). We did not include the External 237 Ecosystems (ECO) variable due to the large geographic scope considered already internal to the case 238 system.

Table 1. Indicators 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)	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)

# 242 **2.3 Survey design and implementation**

243 The primary purpose of the study is to gain insights into the local stakeholder knowledge about the status of the 244 sustainability indicators above. In other words, which indicators do key informant stakeholders believe are stable or 245 unstable in relation to groundwater management, and thus shaping sustainability outcomes? Rather than collecting 246 observational data on all 52 indicators, we conducted a stakeholder survey with 22 locally informed expert key 247 informants who are affiliated with the two important agricultural and water management organizations (Appendix 248 Table S2). We asked each to indicate, to their knowledge, the status of the indicator in relation to current 249 groundwater management. Each key informant is involved in either the Agriculture Organization or the Regional 250 Water Organization of Hamedan-Bahar. For each indicator, an 11-point Likert scale was provided. Collecting local expert knowledge enables drawing on local expertise while co-producing knowledge through an inclusive 251 methodology. The survey was constructed and distributed in Persian. A translated sample of the survey is provided 252 253 in English for reference (Appendix Table S1). The Likert rating of each indicator provided a standardized response 254 format for statistical analysis, and allowed us to identify which indicators within the 7 SESF first-tier variables are 255 perhaps most influential, stable or lacking attention in current water governance practices.

#### 256 **2.4 Data analysis**

A combination of Shannon's entropy weighting and TOPSIS methods was used to analyze the Likert survey data collected. The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is based on calculating the distance between the alternatives from the positive ideal solution (PIS) and negative ideal solution (NIS) (Lin, 2010). 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. In multi-criteria decision-making problems, especially multi-indicator decisionmaking problems, having and knowing the relative weights of the available indicators is an effective step in the problem-solving process and is necessary.

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Shannon's (1948) entropy theory, later put forward by Lie et al., 2010, enables the weighting calculations 272 273 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 274 based on n criteria, weighted using the concept of entropy. If we denote the decision matrix by X and each 275 276 of its roots by xij, first the decision matrix must be normalized. The normalized matrix is denoted by N and 277 each row is denoted by nij (Hakimi et al., 2017). In the Shannon entropy technique, according to the 278 weights obtained from the indicators in this step, indicators that have more relative dispersion, are more 279 important and their influence is greater in choosing the optimal option (Jun et al, 2013).

280

Conducting the full analysis of the data, TOPSIS with Shannon entropy weighting, includes the following 281 steps (Asgharpour, 2021). In the first step, the decision matrix of raw survey data (rows of survey inputs 282 and columns of governance indicators) was descaled (Appendix Figure S1). In the second step, the 283 "weighted scaleless" matrix was created using the formula:  $V = N_{D.} \times W_{m^*n}$  where (v) is a weighted scaleless 284 285 matrix,  $(N_D)$  is 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: 286 Positive ideal alternative =A<sup>+</sup> ={(max V<sub>ij</sub> |  $j \in j$ ), (minV<sub>ij</sub> |  $J \in j$ ) | i=1,2,...m} ={V<sub>1</sub><sup>+</sup>, V<sub>2</sub><sup>+</sup>,...,V<sup>+</sup> i,...,V<sub>n</sub><sup>+</sup>}; Negative 287 ideal alternative =A<sup>-</sup>={(minVij|j∈j),(maxVij|J∈j`) |i=1,...,m} = {V1, V2,...Vn}; j`= {j=1, 2...n, j is relating to 288 the cost}; J={j=1,2,...,n} is relating to the profit}. 289

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293 In the fourth step, the distance was calculated using the Euclidean method as follows. The i-th 294 alternative's distance from the PIS:

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

297 298

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

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301  

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

$$= 1, 2, 3, ..., m$$

302

303 In the fifth step, the ratio of the relative proximity of A<sub>1</sub> was calculated using the following formula:

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

304

Finally, in the sixth step, **cli**<sup>+</sup>, based on the alternatives values, all were ranked and ordered.

306

In order to examine, compare and visually plot the relative importance for sustainability of the aggregate 307 indicator scores in each of the first-tier variables of the SESF, the different resulting quantities were 308 309 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 10<sup>th</sup> (i.e., 0.1)). The minimum 310 311 value was then subtracted from the numerical value of each indicator and divided by the range of the 312 fluctuations to obtain relative scaleless data between zero and one. The ranks zero to 0.2 were considered 313 highly unsustainable; 0.2 to 0.4 unsustainable; 0.4 to 0.6 semi-sustainable; 0.6 to 0.8 sustainable, and 0.8 to 1 highly sustainable. A radar plot was used for comparative visualization (Wong, 2006). 314

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# **316 3.0 Findings**

# 317 **3.1 TOPSIS weighting of indicators**

The criteria were weighted in TOPSIS software using the 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 scores obtained from the average score of the questionnaires. The weights of the indicators were obtained using the 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 positive utility, while the cost index has negative utility. According to the results, the item "illegal 325 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 326 volume of groundwater (0.058), groundwater reservoir deficit (0.052), employment in agricultural sector 327 (0.048), land subsidence (0.047), farmers' abstraction of groundwater resources (0.045), number of 328 exploiting farmers (0.044), population density of farmers in the region (0.04), flood (0.038), groundwater 329 330 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 331 resources in Hamedan-Bahar Plain (Table 2). 332

333

Indicator

Illegal wells (35)	Gov	0.066 (-)
Abstraction volume of groundwater (47)	Outcome	0.058(-)
Groundwater reservoir deficit (48)	Outcome	0.052(-)
Employment in 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)	0	0.038(-)
Groundwater pollution (46)	Outcome	0.037(-)
↑ Negative - Positive ↓ (see Table SX for al	ll 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(+)

SESF

Weighted value

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

#### 337 **3.2** 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), 338 339 which determine the distance of the i-th alternative from the ideal alternative (highest performance of 340 each indicator) with the A<sup>+</sup> sign and determining the distance of the i-th alternative of the minimum 341 alternative (lowest performance of each indicator) with the A sign. Accordingly, the near-ideal alternative 342 will have the minimum distance from the positive ideal state and the maximum distance from the NIS 343 (Cavallaro, 2010). In the next step, the difference or distance of each item is calculated using the Euclidean 344 method (Table SX). 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 345 region, while land subsidence (49), reservoir deficit (48) and groundwater pollution (46) are the next most 346 347 influential indicators, respectively (Table SX).

348

349 Determining the near-ideal alternative involved taking two steps (Table 3). First, the relative proximity of 350 A1 was calculated using the formula between zero and one, with the number one indicating the highest 351 rank and the number zero indicating the lowest rank in the set (Izadi et al., 2010). Next, the alternatives 352 were ranked in an ascending to descending order. The results of applying the weights and calculating the 353 proximity of the alternatives to the ideal solution are presented in Table 4. According to the alternative 354 of the nearest-ideal solution, the results of ranking the indicators show that monitoring agents, watershed management projects, transmission efficiency, and water consumption have the greatest influence on the 355 356 sustainability of groundwater resources in Hamedan-Bahar Plain. In contrast, the numbers of illegal wells, 357 land subsidence, and abstraction volume of groundwater have the most negative influence on groundwater resources in the region. 358

**Table 3**. Ranking of indicators affecting the sustainability of groundwater resources, calculated, ranked and ordered by the indicators with least distance from the positive 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 (GS#39)	Watershed management projects (RS#27)	Efficiency and consump. (RS#25)	Hydrological boundaries (RS #24)	Number of farmers (A#36)	Rainfall (RU#20)	Balance between agri. and env. (RS#26)	Volume of renewable water (RS#23)	Number of media and education prog. (S#15)	Potential of renewable groundwater (RU#21)	Government policies (S#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 (S#18)	Integration of agricultural lands (S#6)	Economic value of groundwater (RU#22)	Number of media (S#14)	Responsibility in water consumption (O#52)	Agriculture groundwater efficiency (O#45)	Number of governmental organizations (GS#28)	Number of NGOs in water (GS#29)	Rural literacy rate (S#13)	Migration rate (S#12)	Communication and interaction of orgs. (GS#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	Interaction between economic sectors (GS#31)	Extent of empowermen t programs (O#51)	Interaction of economic sectors (I#44)	Number of sectors using water (A#37)	New irrigation equipment (S#19)	Number of local water markets (GS#34)	Regulations between farmers (I#43)	Farmer interactions (I#42)	Diversity of products (S#4)	Income distribution (S#3)	Rural per capita income (S#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 (GS#33)	Number of smart meters (GS#32)	Number of social orgs. operating (A#38)	Gender structure (S#11)	Age structure (S#10)	Farmer groundwater demand (S#7)	Integration of agricultural lands (S#5)	Employment in agriculture (S#1)	Disputes and conflicts (S#17)	Farmers' population density (S#9)	Information exchange among farmers (I#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 (S#8)	Social capital of farmers (A#40)	Groundwater deficit (O#48)	Groundwater pollution (O#46)	Number of floods (O#50)	Groundwater use volume (O#47)	Land subsidence (O#49)	Number of illegal wells (GS#35)			
PCI	0.210	0.210	2197	192	0.184	0.155	0.113	0.088			

#### 3.3 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 draw conclusions about 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 to 0.4 unsustainable; 0.4 to 0.6 semi-sustainable; 0.6 to 0.8 sustainable, and 0.8 to 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 Figure 3. 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 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 rate of information exchange between farmers, farmers' interaction about water, farmer agreement, and internal regulations among farmers. 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 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. Th main indicators being efficiency of groundwater resources in agriculture, the extent of farmers' empowerment programs, and responsibility in water consumption. Overall, this analysis suggests that there are both positive and negatively influential indicators shaping the overall sustainability, but that social factors more generally rank lower. A full table of each individual indicator value within each SESF first-tier variable are shown in Appendix Table S5.

**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 to 0.2 (highly unsustainable); 0.2 to 0.4 (unsustainable); 0.4 to 0.6 (semi-sustainable); 0.6 to 0.8 (sustainable), and 0.8 to 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 indictors	5	3	5	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



Figure 3. Radar plot of the average indicator values for each SESF first-tier variable.

# 4.0 Discussion

In this study we demonstrate how using local knowledge to make rapid and comprehensive assessments of social and ecological sustainability is possible and useful for gaining broad insights about a regional groundwater system to inform further studies and local decision-making. Drawing on expert knowledge and applying established analytical tools to structured data provides accessible insights into otherwise data scarce indicators in understudied regions. Integrating local knowledge co-production and provide an inclusive methodological approach that can perhaps better link science and practice by integrating and valuing the inputs of non-science experts (Virapongse et al., 2016; Gurney et al., 2019; Partelow et al., 2019). These frameworks, with Ostrom's SESF arguably being the most well adopted, can organize complex system information in a way that can make data aggregation and communication of results more accessible. Nonetheless, the framework will remain limited in its use without further theoretical and methodological advancements (Cumming et al., 2020), such has attempting co-production processes.

Water governance faces challenges worldwide, and our findings demonstrate that there are a broad range of potentially influential factors that can shape the importance of governance and sustainability outcomes. A main challenge is identifying potential factors and collecting data on each in a way that can provide an initial scientific basis for continued decision-making and research. A main challenge moving forward, both in science and governance, is the evaluation of connections and interdependencies between variables using diverse data (Cumming et al., 2020; Nagel and Partelow, 2022). In other words, there is a need in the current literature to move beyond generating lists of important variables, and to move towards the analysis of variable-variable and further complex system interactions (Villamayor-Tomas et al., 2020). In our analysis we demonstrate how weighting and ranking methods are useful for evaluating impact and prioritizing actions, a step beyond producing a list. Nonetheless, there is a need to develop methods to analyze how those variables interact with each other and co-shape intermediary and final outcomes (Baggio et al., 2016; Villamayor-Tomas et al., 2020).

Specific to our case, we show how social factors are consistently evaluated by local experts as the main factors hindering the sustainable use and management of groundwater. Various reviews of the literature applying the SESF have shown that social factors generally have received more attention across studies, either because most studies are conducted by social scientists interested in examining social issues, or because the social factors in most evaluated cases studies are most influential in shaping social-ecological sustainability (Thiel et al., 2015; Partelow, 2018; Nagel and Partelow, 2022). In the case of groundwater, shown in our case on the Hamedan-Bahar Plain, important RS and RU variables are difficult to change, or cannot be changed such as rainfall, hydrological boundaries or water volume. However, social factors such as illegal wells, use amounts, social capital, information exchange and regulations can be shaped through governance. Weighting and ranking enables us to show which variables have been consistently evaluated as needing attention, suggesting they could be priority areas for governance attention going forward.

As groundwater embodies the characteristics of a common-pool resource, the literature suggests potential governance strategies with many demonstrated cases. For example, establishing effective property rights arrangements such as cooperatives or private quota allocations may help address disputes and conflicts, overuse through perceived scarcity and the interactions between sectors using water (Chen et al.,2018; Jia et al.,2019; Li and Qian,2018; Mirzaei et al.,2020; Sarami et al.,2021). Establishing monitoring and sanctioning strategies can impact the use of illegal wells or excessive use and pollution, and if done by the

water users themselves it may create accountability, trust and responsibility in the system among users while avoiding external conflicts or dependence on, for example, government agencies or NGOs (Boretti and Rosa, 2019; Loucks and van Beek, 2017; Giri and Qiu, 2016). Focusing on bringing different stakeholders together in deliberative settings to discuss challenges, needs, frustrations and potential pathways forward can foster networks of information exchange and transparency in the process of decision-making through inclusion (Meinzen-Dick et al., 2018; Rey et al., 2019; Sanchis-Ibor et al., 2017; Westerink et al., 2017; Yu et al., 2016;). However, this can also create challenges such as conflict and inefficiency, which may require effective facilitation, communication and planning.

More specifically to the Hamedan-Bahar Plain, the indicators of watershed management projects, artificial recharge and water storage are likely the most influential on sustainability. A decrease in the discharge of wells, springs and aqueducts in the plains will disturb the water and environmental equilibrium, an undesired outcome. Artificial recharge of aquifers, like the flood spreading method in the plains, is one strategy that can be used for refilling groundwater aquifers and also plays an important role in rehabilitation of degraded pastures and desertification. Moreover, using the capacity of the underground reservoir to store excess water in the cropping season will be another advantage of this method. Such approaches have been supported by an emerging literature (Floress et al., 2015; Medema et al., 2016; Reddy et al., 2017; Ali et al., 2017; Cai et al., 2018; Yang et al., 2019). An important indicator of RS is efficiency of water transmission systems. Water transmission or transportation is critical within the agricultural sector due to high demand and use. Using canals and pipes with polyethylene fittings, for example, can prevent water loss during transport and increase efficiency through mitigating leakage (Brown et al., 2015; Kotir et al., 2016; Sun et al., 2016; Fang and Chen, 2017; Cai et al., 2018). Furthermore, long-term environmental trends such as known or regularly monitored precipitation patterns and drought cycles, when considered in planning and water allocation, can help mitigate overuse and avoid crop loss (Jiang et al., 2017; Wei et al., 2017; Xie et al., 2018; Bierkens and Wada, 2019; Sulaiman et al., 2019; Hussain et al., 2019; Ahmad and Al-Ghouti, 2020; Luo et al., 2020).

Economic value is another critical factor, a political tool to increase water efficiency, reduce water demand, manage the irrigation systems and regain costs (Brown et al., 2015; Garcia and Pargament, 2015; Hering et al., 2015; Distefano and Kelly, 2017; Pires et al., 2017). The interactions (I) factors, such as the farmers' agreement and interaction on water issues and collective laws is another factor reflecting social capital and how conflicts are resolved or not. Self-organization has consistently been shown in commons literature as a key factor in determining collective action, and thus cooperative activities to govern shared resources and resolve joint problems (Yu et al., 2016; Sanchis-Ibor et al., 2017; Westerink et al., 2017; Meinzen-Dick et al., 2018; Rey et al., 2019).

In the GS criteria, management organizations make regular and periodic inspections of wells, control the amount of water supply and operation, and sanction violators. The installation of smart water meters to measure extraction amounts have helped considerably as well as installing volume meters. Monitoring that leads to more information about the status of the resources, and thus provide a feedback loop on the impact of use can be critically important for behaviour change and governance response (Megdal et al., 2015; Giri and Qiu, 2016; Sun et al., 2016; Ashraf et al., 2017; Loucks and van Beek, 2017; Brendel et al., 2018; Boretti and Rosa, 2019; Singh and Bhakar, 2021). Broader criteria in the Social, Economic and Political Settings (S) include media communication through radio, internet and television about programs and trainings (Butler and Adamowski, 2015; Sivapalan and Blöschl, 2015; Cominola et al., 2015; Arthington et al., 2018).

# 6. Conclusion

Using local expert knowledge to examine and rank the factors influencing social-ecological system sustainability is an effective way to provide a broad assessment of wide ranging indicators while also valuing local knowledge. By applying multi-criteria decision making tools such as TOPSIS and Shannon entropy, we can provide a weighted and ranked list of indicators that have been locally evaluated as influential in local groundwater governance and sustainability. Our findings suggest that social factors likely require the most attention in further governance efforts to better examine how and why groundwater is used to meet sustainability goals. Nonetheless, our study has also shown that a full assessment of all potential social-ecological factors in a groundwater system, guided by Ostrom's social-ecological systems framework (SESF), is important for gaining a systems perspective that considers potentially unforeseen factors and their potential interactions. Further steps forward include reflection of findings with local managers and policy makers while also informing continued analysis of the interactions between key indicators, particularly social factors such as monitoring, social capital, regulation and overuse, to improve understandings of existing problems and potential solutions.

# References

- Ahmad, A. Y., Al-Ghouti, M. A., 2020. Approaches to achieve sustainable use and management of groundwater resources in Qatar: a review. Groundwater for Sustainable Development, 11, 100367.
- Ali, A. M., Shafiee, M. E., & Berglund, E. Z. (2017). Agent-based modeling to simulate the dynamics of urban water supply: Climate, population growth, and water shortages. *Sustainable Cities and Society*, 28, 420-434.
- Andersson, D., Bratsberg, S., Ringsmuth, A. K., & de Wijn, A. S. (2021). Dynamics of collective action to conserve a large common-pool resource. Scientific reports, 11(1), 1-11.
- Arjmand, M., Sadeghian Pir Mahalleh, N., Amini, S., Nazarnia Kharajoo, S., 2020. Study of the laws governing the groundwater of Iran. Journal of Civil Engineering and Project,2(2),23-29.
- Arthington, A.H., Bhaduri, A., Bunn, S.E., Jackson, S.E., Tharme, R.E., Tickner, D., Young, B., Acreman, M., Baker, N., Capon, S., Horne, A.C., 2018. The Brisbane declaration and global action agenda on environmental flows. Frontiers in Environmental Science, 6, p.45
- Asgharpour. M. J. (2021). Multi-criteria decision making, Published by University of Tehran press. (In Farsi)
- Ashraf, B., AghaKouchak, A., Alizadeh, A., Mousavi Baygi, M., R Moftakhari, H., Mirchi, A., Anjileli, H., Madani, K., 2017. Quantifying anthropogenic stress on groundwater resources. Scientific reports, 7(1), 1-9.
- Asprilla-Echeverria, J., 2021. The social drivers of cooperation in groundwater management and implications for sustainability. Groundwater for Sustainable Development, 15, 100668.
- Bäckstrand K (2004) Civic Science for Sustainability: Reframing the Role of Experts, Policy-Makers and Citizens in Environmental Governance. Glob Environ Polit 24–42
- Baggio JA, Barnett AJ, Perez-Ibara I, et al (2016) Explaining success and failure in the commons: the configural nature of Ostrom's institutional design principles. Int J Commons 10:. https://doi.org/10.18352/ijc.634
- Bai, T., Chang, J.X., Chang, F.J., Huang, Q., Wang, Y.M., Chen, G.S., 2015. Synergistic gains from the multiobjective optimal operation of cascade reservoirs in the Upper Yellow River basin. Journal of Hydrology, 523, 758-767.
- Barnett AJ, Partelow S, Frey U, et al (2020) Defining Success in the Commons: Addressing Problem Orientations, Multidimensionality, Norms, and Tradeoffs. Int J Commons 14:366–387. https://doi.org/https://doi.org/10.5334/ijc.994
- Basurto, X., Gelcich, S. Ostrom, E., 2013. The social-ecological system framework as a knowledge classificatory system for benthic small-scale fisheries. Global environmental change, 23(6), 1366-1380.
- Bergstrom, D.M., Wienecke, B.C., van den Hoff, J., Hughes, L., Lindenmayer, D.B., Ainsworth, T.D., Baker, C.M., Bland, L., Bowman, D.M., Brooks, S.T., Canadell, J.G., 2021. Combating ecosystem collapse from the tropics to the Antarctic. Global Change Biology, 27(9), 1692-1703.
- Bierkens, M. F., Wada, Y., 2019. Non-renewable groundwater use and groundwater depletion: a review. Environmental Research Letters, 14(6), 063002.
- Bluemling, B., Tai, H. S., Choe, H., 2021. Boundaries, limits, landscapes and flows: An analytical framework for boundaries in natural resource management. Journal of Environmental Management, 285, 112129.

- Bogardi, J. J., Bharati, L., Foster, S., Dhaubanjar, S., 2021. Water and Its Management: Dependence, Linkages and Challenges. In Handbook of Water Resources Management: Discourses, Concepts and Examples (pp. 41-85). Springer, Cham.
- Boretti, A., Rosa, L., 2019. Reassessing the projections of the world water development report. NPJ Clean Water, 2(1), 1-6.
- Brendel, S., Fetter, É., Staude, C., Vierke, L., Biegel-Engler, A., 2018. Short-chain perfluoroalkyl acids: environmental concerns and a regulatory strategy under REACH. Environmental Sciences Europe, 30(1), 1-11.
- Brown, C.M., Lund, J.R., Cai, X., Reed, P.M., Zagona, E.A., Ostfeld, A., Hall, J., Characklis, G.W., Yu, W., Brekke, L., 2015. The future of water resources systems analysis: Toward a scientific framework for sustainable water management. Water resources research, 51(8), 6110-6124.
- Butler, C., Adamowski, J., 2015. Empowering marginalized communities in water resources management: Addressing inequitable practices in Participatory Model Building. Journal of Environmental Management, 153, 153-162.
- Cai, X., Wallington, K., Shafiee-Jood, M., Marston, L., 2018. Understanding and managing the food-energywater nexus-opportunities for water resources research. Advances in Water Resources, 111, 259-273.
- Cámara-Leret R, Dennehy Z (2019) Information gaps in indigenous and local knowledge for science-policy assessments. Nat Sustain 2:736–741. <u>https://doi.org/10.1038/s41893-019-0324-0</u>
- Carpenter, S. R, Arrow, K. J, Barrett, S, Biggs, R, Brock, W. A, Crépin, A. S, Engström, G, Folke, C, Hughes, T. P, Kautsky, N, Li, C.-Z, McCarney, G, Meng, K, Mäler, K.-G, Polasky, S, Scheffer, M, Shogren, J, Sterner, T, Vincent, J. R, Walker, B, Xepapadeas, A., Zeeuw, A. D., 2012. General Resilience to Cope with Extreme Events.Sustainability, :(12) 4 43259–3248.
- Cavallaro, F., 2010. A comparative assessment of thin-film photovoltaic production processes using the ELECTRE III method. Energy Policy, 38(1), 463-474.
- Chen, J., Wu, H., Qian, H., Li, X., 2018. Challenges and prospects of sustainable groundwater management in an agricultural plain along the Silk Road Economic Belt, north-west China. International Journal of Water Resources Development, 34(3), 354-368.
- Colding, J., Barthel, S., 2019. Exploring the social-ecological systems discourse 20 years later. Ecology and Society 24(1), 2.
- Cole, D.H., Epstein, G., McGinnis, M.D., 2014. Digging deeper into Hardin's pasture: the complex institutional structure of 'the tragedy of the commons'. Journal of Institutional Economics, 10(3), pp.353-369.
- Cominola, A., Giuliani, M., Piga, D., Castelletti, A., Rizzoli, A. E., 2015. Benefits and challenges of using smart meters for advancing residential water demand modeling and management: A review. Environmental Modelling & Software, 72, 198-214.
- Cumming GS, Epstein G, Anderies JM, et al (2020) Advancing understanding of natural resource governance: a post-Ostrom research agenda. Curr Opin Environ Sustain 26–34. https://doi.org/10.1016/j.cosust.2020.02.005
- Cumming, G. S., Olsson, P., Chapin, F.S., Holling, C. S., 2013. Resilience, Experimentation, and Scales Mismatches in Social-Ecological Landscapes .Landscape Ecology.1150–1139 :28
- Di, D., Wu, Z., Wang, H., Zhang, F., 2022. Spatial pattern analysis on the functions of water resources economic-social-ecological complex system. Journal of Cleaner Production, 336, p.130323.
- Distefano, T., Kelly, S., 2017. Are we in deep water? Water scarcity and its limits to economic growth. Ecological Economics, 142, 130-147.
- Elshall AS, Arik AD, El-Kadi AI, et al (2020) Groundwater sustainability: A review of the interactions between science and policy. Environ Res Lett 15:. https://doi.org/10.1088/1748-9326/ab8e8c
- Eman, K., Meško, G., 2021. Water Crimes and Governance: The Slovenian Perspective. International Criminology, 1(3), 208-219.

- Esteban, E., 2021. Emerging Issues in Groundwater Sustainability: New Challenges. In Oxford Research Encyclopedia of Environmental Science.
- Fang, D., Chen, B., 2017. Linkage analysis for the water-energy nexus of city. Applied energy, 189, 770-779.
- Feng, Z. K., Liu, S., Niu, W. J., Li, B. J., Wang, W. C., Luo, B., Miao, S. M., 2020. A modified sine cosine algorithm for accurate global optimization of numerical functions and multiple hydropower reservoirs operation. Knowledge-Based Systems, 208, 106461
- Fereshtehpour, M., Roghani, B., Mianabadi, H., 2016.Geopolitical Challenges of Transboundary Ground Water Resources Governance; With Emphasis on Iran.international quarterly of geopolitics.11(39), 170-204.
- Floress, K., Akamani, K., Halvorsen, K. E., Kozich, A. T., Davenport, M., 2015. The role of social science in successfully implementing watershed management strategies. Journal of Contemporary Water Research & Education, 154(1), 85-105.
- Garcia, X., Pargament, D., 2015. Reusing wastewater to cope with water scarcity: Economic, social and environmental considerations for decision-making. Resources, Conservation and Recycling, 101, 154-166.
- Ghorbani, A., & Bravo, G. (2016). Managing the commons: a simple model of the emergence of institutions through collective action. International Journal of the Commons, 10(1).
- Giri, S., Qiu, Z., 2016. Understanding the relationship of land uses and water quality in twenty first century: a review. Journal of environmental management, 173, 41-48.
- Gleeson T, Cuthbert M, Ferguson G, Perrone D (2020) Global Groundwater Sustainability, Resources, and Systems in the Anthropocene
- Gurney GG, Darling ES, Jupiter SD, et al (2019) Implementing a social-ecological systems framework for conservation monitoring: lessons from a multi-country coral reef program. Biol Conserv 240:. https://doi.org/10.1016/j.biocon.2019.108298
- Hakimi, A., Hosseini Amiri, S.M. and Nafshad, A., 2017, Shannon entropy weighting technique: a weighting tool decision making for project analysts, the second international management and accounting conference. Iran Tehran,
- Hering, D., Carvalho, L., Argillier, C., Beklioglu, M., Borja, A., Cardoso, A.C., Duel, H., Ferreira, T., Globevnik,
  L., Hanganu, J., Hellsten, S., 2015. Managing aquatic ecosystems and water resources under multiple stress—An introduction to the MARS project. Science of the total environment, 503, 10-21.
- Holling, C. S., 2003. The Backloop to Sustainability. In: Berkes, F, Colding, J and Folke, C eds., editors .Navigating Social-Ecological Systems: Building Resilience for Complexity and Change .Cambridge: Cambridge University Press. p. xv.-xxi
- Holling, C. S., Meffe, G. K., 1996. Command and Control and the Pathology of Natural Resource Management. Conservation Biology, 10(2), 328–337.
- Hussain, M. I., Muscolo, A., Farooq, M., Ahmad, W., 2019. Sustainable use and management of nonconventional water resources for rehabilitation of marginal lands in arid and semiarid environments. Agricultural water management, 221, 462-476.
- Izadi, M., Abolhasani, F., Nastaran, M., 2010. Application of TOPSIS method in analysis and prioritizing sustainable development of urban zones (case study: urban zones of Isfahan). Geography and Enviromental Planning. 21(2), 83-100.
- Jia, X., O'Connor, D., Hou, D., Jin, Y., Li, G., Zheng, C., Ok, Y.S., Tsang, D.C. Luo, J., 2019. Groundwater depletion and contamination: Spatial distribution of groundwater resources sustainability in China. Science of the Total Environment, 672, 551-562
- Jiang, S., Wang, J., Zhao, Y., Shang, Y., Gao, X., Li, H., Wang, Q., Zhu, Y., 2017. Sustainability of water resources for agriculture considering grain production, trade and consumption in China from 2004 to 2013. Journal of Cleaner Production, 149, 1210-1218.

- Jun, K.S. Chung, ES. Kim, Y.G and Kim, Y. (2013). A Fuzzy multi-criteria approach to flood risk vulnerability in south korea by considering climate change impacts. Expert systems with applications, 40 1003-1013.
- Katz, D., 2021. Desalination and hydrodiplomacy: Refreshening transboundary water negotiations or adding salt to the wounds? Environmental Science & Policy, 116, 171-180
- Knüppe, K., Meissner, R., 2016. Drivers and barriers towards sustainable water and land management in the Olifants-Doorn Water Management Area, South Africa. Environmental Development, 20, 3-14.
- Kotir, J. H., Smith, C., Brown, G., Marshall, N., Johnstone, R., 2016. A system dynamics simulation model for sustainable water resources management and agricultural development in the Volta River Basin, Ghana. Science of the Total Environment, 573, 444-457.
- Li, P., & Qian, H. (2018). Water resources research to support a sustainable China. International Journal of Water Resources Development, 34(3), 327-336.
- Li, P., Qian, H. and Wu, J.H., 2010. Groundwater quality assessment based on improved water quality index in Pengyang County, Ningxia, North west China. European Journal of Chemistry. 7, 209–216.
- Li, Y., Li, Y., Kappas, M., Pavao-Zuckerman, M., 2018. Identifying the key catastrophic variables of urban social-environmental resilience and early warning signal. Environment international, 113, 184-190.
- Lin, H.T., 2010. Fuzzy application in service quality analysis: An empirical study. Expert Systems with Applications. 37(1), 517-526.
- Liu, J., Li, M., Wu, M., Luan, X., Wang, W., Yu, Z., 2020. Influences of the south-to-north water diversion project and virtual water flows on regional water resources considering both water quantity and quality. Journal of Cleaner Production, 244, p.118920.
- Loucks, D. P., van Beek, E., 2017. Water resources planning and management: An overview. Water Resource Systems Planning and Management, 1-49.
- Luker, E., 2017. Transitioning towards water supply diversification: possibilities for groundwater in Cape Town, South Africa (Doctoral dissertation, University of British Columbia).
- Luo, P., Sun, Y., Wang, S., Wang, S., Lyu, J., Zhou, M., Nakagami, K., Takara, K., Nover, D., 2020. Historical assessment and future sustainability challenges of Egyptian water resources management. Journal of Cleaner Production, 263, 121154.
- Madani, K., Lund, J. 2012. California's Sacramento-San Joaquin Delta conflict: from Cooperation to Chicken. ASCE Journal of Water Resources Planning and Management, 138 (2), 90-99.
- Mazaheri, M., Abdul Manafi, N. S. A., 2017. Study of water crisis and its consequences in the country. Deputy of Infrastructure Research and Production Affairs, Water Department, serial number: 15608.
- McGinnis, M., Ostrom, E., 2014. Social-ecological system framework: initial changes and continuing challenges. Ecology and Society, 19(2), 30.
- Medema, W., Furber, A., Adamowski, J., Zhou, Q., Mayer, I., 2016. Exploring the potential impact of serious games on social learning and stakeholder collaborations for transboundary watershed management of the St. Lawrence River Basin. Water, 8(5), 175.
- Megdal, S. B., Gerlak, A. K., Varady, R. G., Huang, L. Y., 2015. Groundwater governance in the United States: Common priorities and challenges. Groundwater, 53(5), 677-684.
- Meinzen-Dick, R., Janssen, M. A., Kandikuppa, S., Chaturvedi, R., Rao, K., Theis, S., 2018. Playing games to save water: Collective action games for groundwater management in Andhra Pradesh, India. World Development, 107, 40-53.
- Mirzaei, A., Knierim, A., Nahavand, S. F., Shemshad, M., 2020. The role of social capital in water reservoirs governance: evidence from northern Iran. Human Ecology, 48(4), 491-503.
- Mishra, B. K., Kumar, P., Saraswat, C., Chakraborty, S., Gautam, A., 2021. Water security in a changing environment: Concept, challenges and solutions. Water, 13(4), 490.
- Molden, D., Lautze, J., Shah, T., Bin, D., Giordano, M., & Sanford, L. (2010). Governing to grow enough food without enough water—second best solutions show the way. International Journal of Water Resources Development, 26(2), 249-263.

Montenegro, L., Hack, J., 2020. "A Socio-Ecological System Analysis of Multilevel Water Governance in Nicaragua" Water 12, no. 6: 1676. https://doi.org/10.3390/w12061676

Nagel B, Partelow S (2022) A methodological guide for applying the SES framework: a review of quantitative approaches. Ecol Soc (In press)

Nagendra, H., Ostrom, E., 2014. Applying the social-ecological system framework to the diagnosis of urban lake commons in Bangalore, India. Ecology and Society, 19(2).

Ndlovu, S., Sibanda, M., Motsholapheko, D., 2022. Hydronyms of pools along Gweru River in the silobela district of Zimbabwe as holistic indigenous knowledge (IK) for integrated water resources management. Physics and Chemistry of the Earth, Parts A/B/C, 125, 103104.

- Newig J, Fritsch O (2009) Environmental governance: Participatory, multi-level And effective? Environ Policy Gov 19:197–214. https://doi.org/10.1002/eet.509
- OECD (2015) Stakeholder engagement for inclusive water governance. Paris, OECD Publishing.
- Omranian Khorasani, H., 2015. Good governance and water management. Journal of Water and Sustainable Development. 1(3). 94-95.

Orach, K., Schlüter, M., 2016. Uncovering the political dimension of social-ecological systems: Contributions from policy process frameworks. Global Environmental Change, 40, 13-25.

- Ostrom E (1965) Public Entrepreneurship: A Case Study in Ground Water Basin Management. UCLA
- Ostrom E (1998) A Behavioral Approach to the Rational Choice Theory of Collective Action. Am Polit Sci Rev 92:1–22. https://doi.org/10.2307/2585925
- Ostrom, E., 1990. Governing the commons, the evolution of institutions for collective action. New York: Cambridge University.
- Ostrom, E., 2009. Beyond markets and states: Polycentric governance of complex economy systems. Indiana: Indiana University.
- Palomo, L. E., Hernández-Flores, A., 2019. Application of the Ostrom framework in the analysis of a socialecological system with multiple resources in a marine protected area. Peer J, 7, e7374.
- Pandey VP, Shrestha S, Chapagain SK, Kazama F (2011) A framework for measuring groundwater sustainability. Environ Sci Policy 14:396–407. <u>https://doi.org/10.1016/j.envsci.2011.03.008</u>

Partelow S (2018) A review of the social-ecological systems framework: applications, methods, modifications, and challenges. Ecol Soc 23:. https://doi.org/10.5751/ES-10594-230436

- Partelow S (2020) Analyzing natural resource governance with the social-ecological systems framework. In: Nunan F (ed) Governing Renewable Natural Resources: Theories and Frameworks. Routledge, London and New York
- Partelow S, Fujitani M, Soundararajan V, Schlüter A (2019) Transforming the social-ecological systems framework into a knowledge exchange and deliberation tool for comanagement. Ecol Soc 24:. https://doi.org/10.5751/ES-10724-240115
- Partelow S, Jäger A, Schlüter A (2021) Linking Fisher Perceptions to Social-Ecological Context: Mixed Method Application of the SES Framework in Costa Rica. Hum Ecol 49:187–203
- Partelow, S., Schlüter, A., O Manlosa, A., Nagel, B., & Octa Paramita, A. (2022). Governing aquaculture commons. *Reviews in Aquaculture*, 14(2), 729-750.
- Pires, A., Morato, J., Peixoto, H., Botero, V., Zuluaga, L., Figueroa, A., 2017. Sustainability Assessment of indicators for integrated water resources management. Science of the total environment, 578, 139-147.
- Prescott-Allen R (1996) Barometer of Sustainability: What it's for and how to use it. IUCN. Gland, Switzerland.
- Reddy, V. R., Saharawat, Y. S., George, B., 2017. Watershed management in South Asia: A synoptic review. Journal of hydrology, 551, 4-13.

- Reed MS (2008) Stakeholder participation for environmental management: A literature review. Biol Conserv 141:2417–2431. https://doi.org/10.1016/j.biocon.2008.07.014
- Rey, D., Pérez-Blanco, C. D., Escriva-Bou, A., Girard, C., Veldkamp, T. I., 2019. Role of economic instruments in water allocation reform: lessons from Europe. International Journal of Water Resources Development, 35(2), 206-239.
- Robertson, J., 2021. The Common Pool Resource Heatmap: A Tool to Drive Changes in Water Law and Governance. Water, 13, 3110.
- Sanchis-Ibor, C., Boelens, R., Garcia-Molla, M., 2017. Collective irrigation reloaded. Re-collection and remoralization of water management after privatization in Spain. Geoforum, 87, 38-47.
- Sarami Foroushani, T., Balali, H., Movahedi, R., 2021. Evaluation of Groundwater Resources Governance Indicators in Iran's Agricultural Sector: Application of the OECD Governance Framework in the Hamadan-Bahar Plain. Iranian Agricultural Economics and Development Research, 52 (3), 591-615. doi: 10.22059 / ijaedr.2021.313265.668972
- Schneider F, Buser T (2017) Promising degrees of stakeholder interaction in research for sustainable development. Sustain Sci. <u>https://doi.org/10.1007/s11625-017-0507-4</u>
- Shannon, E., 1948. A mathematical theory of communication. The Bell System Technical Journal. 27, 379– 423
- Singh, A. P., Bhakar, P., 2021. Development of groundwater sustainability index: a case study of western arid region of Rajasthan, India. Environment, development and sustainability, 23(2), 1844-1868.
- Sivapalan, M., Blöschl, G., 2015. Time scale interactions and the coevolution of humans and water. Water Resources Research, 51(9), 6988-7022.
- Sterling EJ, Betley E, Sigouin A, et al (2017) Assessing the evidence for stakeholder engagement in biodiversity conservation. Biol Conserv 209:159–171. <u>https://doi.org/10.1016/j.biocon.2017.02.008</u>
- Sulaiman, S. O., Kamel, A. H., Sayl, K. N., Alfadhel, M. Y., 2019. Water resources management and sustainability over the Western desert of Iraq. Environmental Earth Sciences, 78(16), 1-15.
- Sun, S., Wang, Y., Liu, J., Cai, H., Wu, P., Geng, Q., Xu, L., 2016. Sustainability assessment of regional water resources under the DPSIR framework. Journal of Hydrology, 532, 140-148.
- Tengö M, Hill R, Malmer P, et al (2017) Weaving knowledge systems in IPBES, CBD and beyond—lessons learned for sustainability. Curr Opin Environ Sustain 26–27:17–25. <u>https://doi.org/10.1016/j.cosust.2016.12.005</u>
- Thiel A, Adamseged ME, Baake C (2015) Evaluating an instrument for institutional crafting: How Ostrom's social-ecological systems framework is applied. Environ Sci Policy 53:. https://doi.org/10.1016/j.envsci.2015.04.020
- Vener, B.B., 2007. The Kura-Araks Basin: Obstacles and common objectives for an integrated water resources management model among Armenia, Azerbaijan, and Georgia.
- Villamayor-Tomas S, Oberlack C, Epstein G, et al (2020) Using case study data to understand SES interactions: a model-centered meta-analysis of SES Framework applications. Curr Opin Environ Sustain 44:48–57. https://doi.org/10.1016/j.cosust.2020.05.002
- Villamayor-Tomas S, Thiel A, Villamayor-Tomas S, et al (2014) From Sandoz to Salmon: Conceptualizing resource and institutional dynamics in the Rhine watershed through the SES framework. Int J Commons 8:2
- Virapongse A, Brooks S, Metcalf EC, et al (2016) A social-ecological systems approach for environmental management. J Environ Manage 178:83–91. https://doi.org/10.1016/j.jenvman.2016.02.028
- Vogt JM, Epstein GB, Mincey SK, et al (2015) Putting the "E" in SES : unpacking the ecology in the Ostrom social-ecological system framework. Ecol Soc 20:. https://doi.org/10.5751/ES-07239-200155
- Wehn U, Collins K, Anema K, et al (2018) Stakeholder engagement in water governance as social learning: lessons from practice. Water Int 43:34–59. <u>https://doi.org/10.1080/02508060.2018.1403083</u>

- Wei, J., Wei, Y., Western, A., 2017. Evolution of the societal value of water resources for economic development versus environmental sustainability in Australia from 1843 to 2011. Global Environmental Change, 42, 82-92.
- Westerink, J., Jongeneel, R., Polman, N., Prager, K., Franks, J., Dupraz, P., Mettepenningen, E., 2017. Collaborative governance arrangements to deliver spatially coordinated agri-environmental management. Land Use Policy, 69, 176-192.
- Wong, C., 2006. Indicators for Urban and Regional Planning. Published by Routledge. ISBN 10: 0415274524
- Xie, Y. L., Xia, D. X., Ji, L., Huang, G. H., 2018. An inexact stochastic-fuzzy optimization model for agricultural water allocation and land resources utilization management under considering effective rainfall. Ecological indicators, 92, 301-311.
- Xu, K., Bin, L., Xu, X., 2019. Assessment of water resources sustainability in mainland China in terms of water intensity and efficiency. Environmental management, 63(3), 309-321.
- Yan, H., Sun, N., Wigmosta, M., Skaggs, R., Hou, Z., Leung, R., 2018. Next-generation intensity-durationfrequency curves for hydrologic design in snow-dominated environments. Water Resources Research, 54(2), 1093-1108.
- Yang, Z., Song, J., Cheng, D., Xia, J., Li, Q., Ahamad, M. I., 2019. Comprehensive evaluation and scenario simulation for the water resources carrying capacity in Xi'an city, China. Journal of environmental management, 230, 221-233.
- Ye, Q., Li, Y., Zhuo, L., Zhang, W., Xiong, W., Wang, C., Wang, P., 2018. Optimal allocation of physical water resources integrated with virtual water trade in water scarce regions: A case study for Beijing, China. Water research, 129, 264-276.
- Yu, H. H., Edmunds, M., Lora-Wainwright, A., Thomas, D., 2016. Governance of the irrigation commons under integrated water resources management-A comparative study in contemporary rural China. Environmental Science & Policy, 55, 65-74.
- Zogheib, C., Ochoa-Tocachi, B. F., Paul, J. D., Hannah, D. M., Clark, J., Buytaert, W., 2018. Exploring a water data, evidence, and governance theory. Water Security, 4, 19-25
- Zwarteveen M, Kuper M, Olmos-Herrera C, et al (2021) Transformations to groundwater sustainability: from individuals and pumps to communities and aquifers. Curr Opin Environ Sustain 49:88–97. <u>https://doi.org/10.1016/j.cosust.2021.03.004</u>

# APPENDIX

**Table S1** - Survey distributed for indicator scoring. Below is an English translated example of the original survey forthe (S) variables, with all other variables following the same format.

SESF	Indicators	Score 0 - 10
first-tier		0 unstable $\leftrightarrow \rightarrow$ 10 stable
	Employment in agriculture	0 1 2 3 4 5 6 7 8 9 10

	Rural per capita income	0 1 2 3 4 5 6 7 8 9 10
	Income distribution	0 1 2 3 4 5 6 7 8 9 10
	Diversity of products in the region	0 1 2 3 4 5 6 7 8 9 10
	Market access	0 1 2 3 4 5 6 7 8 9 10
	integration of agricultural lands	0 1 2 3 4 5 6 7 8 9 10
	Farmers 'demand for groundwater resources	0 1 2 3 4 5 6 7 8 9 10
	Population growth rate in the region	0 1 2 3 4 5 6 7 8 9 10
Social	Farmers' population density in the region	0 1 2 3 4 5 6 7 8 9 10
Economic,	Age structure	0 1 2 3 4 5 6 7 8 9 10
and Political Settings (S)	Gender structure	0 1 2 3 4 5 6 7 8 9 10
	Migration rate	0 1 2 3 4 5 6 7 8 9 10
	Rural literacy rate	0 1 2 3 4 5 6 7 8 9 10
	Number of media	0 1 2 3 4 5 6 7 8 9 10
	Number of media and educational programs in water resources	0 1 2 3 4 5 6 7 8 9 10
	Disputes and conflicts in the field of water resources	0 1 2 3 4 5 6 7 8 9 10
	Government policies in the field of water resources	0 1 2 3 4 5 6 7 8 9 10
	Installation of smart water meters	0 1 2 3 4 5 6 7 8 9 10
	New irrigation equipment such as pressurized irrigation	0 1 2 3 4 5 6 7 8 9 10

Figure S1. Decision matrix. Format of raw data from survey for TOPSIS analysis.

	$\mathbf{X}_1$	$X_2$	•	$\mathbf{X}_{j}$	•	X <sub>n</sub>
A <sub>1</sub>	r <sub>11</sub>	r <sub>12</sub>	•	•	•	$\mathbf{r}_{1n}$
$A_2$	r <sub>21</sub>	r <sub>22</sub>	•			$\mathbf{r}_{2n}$
•				•		
Ai	$\mathbf{r}_{i1}$		•	$\mathbf{r}_{ij}$	•	r <sub>in</sub>
•	•	•	•	•		•
A <sub>m</sub>	r <sub>m1</sub>	r <sub>m2</sub>				r <sub>mn</sub>

 Table S2. Key informant profiles who provided survey inputs.

Job	Level of Education	Number	Organization	Specialty
Managers	P.H.D	5	Regional Water/ Agriculture Organization	Groundwater studies
				Protection and exploitation
Expert staff	Masters	17	Regional Water /Agriculture Organization	Planning and economic reviews

 Table S3. Weight of all 52 indicators using Entropy Shannon.

Indicators	1 (-)	2	3	4	5	6	7 (-)	8	9 (-)	10	11	12	13
Weight	<u>0.048</u>	0.006	0.009	0.006	0.02	0.01	<u>0.045</u>	<u>0.032</u>	<u>0.04</u>	0.018	0.019	0.014	0.019
Indicators	14	15	16	17 (-)	18	19	20	21	22	23	24	25	26
Weight	0.011	0.005	0.008	<u>0.036</u>	0.008	0.016	0.006	0.014	0.009	0.006	0.005	0.004	0.006
Indicators	27	28	29	30	31	32	33	34	35 (-)	36	37	38	39
Weight	0.01	0.006	0.006	0.010	0.008	0.017	0.020	0.011	<u>0.066</u>	0.007	0.002	0.018	0.008
Indicators	40 (-)	41	42	43	44	45	46 (-)	47 (-)	48 (-)	49 (-)	50 (-)	51	52
Weight	<u>0.044</u>	0.023	0.008	0.008	0.008	0.009	<u>0.037</u>	<u>0.058</u>	<u>0.052</u>	<u>0.047</u>	<u>0.038</u>	0.016	0.012

Indicators	1	2	3	4	5	6	7	8	9	10	11	12	13
A+	0.038	0.023	0.023	0.022	0.034	0.014	0.038	0.039	0.038	0.033	0.033	0.017	0.018
А-	0.017	0.022	0.022	0.024	0.017	0.039	0.019	0.010	0.015	0.017	0.018	0.034	0.037
Indicators	14	15	16	17	18	19	20	21	22	23	24	25	26
$\mathbf{A}$ +	0.014	0.012	0.013	0.036	0.013	0.020	0.011	0.013	0.015	0.012	0.010	0.009	0.011
А-	0.037	0.038	0.038	0.015	0.038	0.030	0.039	0.040	0.039	0.038	0.038	0.038	0.038
Indicators	27	28	29	30	31	32	33	34	35	36	37	38	39
$\mathbf{A}$ +	0.009	0.014	0.014	0.016	0.017	0.028	0.025	0.020	0.042	0.011	0.018	0.033	0.009
А-	0.039	0.031	0.031	0.030	0.031	0.018	0.024	0.026	0.004	0.038	0.028	0.019	0.039
Indicators	40	41	42	43	44	45	46	47	48	49	50	51	52
$\mathbf{A}$ +	0.039	0.037	0.021	0.020	0.017	0.015	0.040	0.042	0.040	0.041	0.038	0.019	0.015
А-	0.01	0.012	0.026	0.026	0.030	0.036	0.009	0.007	0.01	0.005	0.008	0.035	0.037

**Table** S4. Positive and negative ideal states of each indicator. The best option will have the least distance from the<br/>positive ideal solution and the greatest distance from the negative ideal solution.

 Table S5. Individual indicator values for each SESF first-tier grouping, used to calculate the average weight.

RS	$RS_{1=}0.7, RS_{2=}0.7, RS_{3=}0.8, RS_{4=}0.7, RS_{5=}0.8$
RU	RU <sub>1=</sub> 0.7, RU <sub>2=</sub> 0.7, RU <sub>3=</sub> 0.7
I	I <sub>1</sub> =0.6, I <sub>2</sub> =0.6, I <sub>3</sub> =0.6, I <sub>4</sub> =0.6,
GS	$GS_{1=}0.3,GS_{2=}0.4,GS_{3=}0.5,GS_{4=}0.08,GS_{5=}0.7,GS_{6=}0.6,GS_{7=}0.3,GS_{8=}0.8$
S	$S_{1=}0.3, S_{2=}0.4, S_{3=}0.4, S_{4=}0.5, S_{5=}0.3, S_{6=}0.3, S_{7=}0.7, S_{8=}0.3, S_{9=}0.2, S_{10=}0.2, S_{11=}0.3, S_{12=}0.3, S_{13=}0.6, S_{14=}0.6, S_{15=}0.7, S_{16=}0.7, S_{17=}0.7, S_{18=}0.3, S_{19=}0.5$
А	A <sub>1=</sub> 0.2, A <sub>2=</sub> 0.2, A <sub>3=</sub> 0.5, A <sub>4=</sub> 0.5, A <sub>5=</sub> 0.6
0	$O_1=0.7, O_2=0.1, O_3=0.1, O_4=0.1, O_5=0.1, O_6=0.6, O_7=0.7 O_8=0.1$