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Generation of Potential Sites for Sustainable Water Harvesting Techniques in Oum Zessar Watershed, South East Tunisia

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Abstract: Water harvesting techniques (WHTs) are important climate change adaptation measures to better manage rainwater for domestic and agricultural purposes, but which WHT to plan where is subject to sustainability considerations. Moreover, suitability of different WHTs varies from one location to another, depending on physical and socio-economic conditions. This study aimed to identify suitable sites for WHTs taking into account stakeholders' sustainability criteria. In a participatory assessment framework, Geographic Information Systems and the "Simple Multi-Attribute Rating Technique" were combined to generate suitability maps and to guide sustainable WHTs investments. Steps included the calculation of a sustainability index for a set of traditional and newly introduced WHTs from the perspective of two stakeholder groups, farmers and decision-makers, and its integration with layers of biophysical constraints. An application of the framework in the Oum Zessar watershed, southeast Tunisia, shows that traditional techniques are the most suitable and sustainable for farmers and fall within the highly suitable class in 76.4% of the total area, while decision-makers prefer innovative techniques that are highly suitable in 80.4% of the watershed. The framework offers a scalable transparent process for knowledge integration in support of WHT investment decisions that can be adapted to other dryland areas.

Keywords: GIS; rainwater harvesting; composite sustainability indicator; spatial multi-criteria analysis; Tunisia

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1. Introduction

Water availability is becoming an increasingly limiting factor for economic, social and environmental sustainability in arid and semi-arid regions worldwide [1–3]. It has been confirmed that an Integrated Water Resources Management approach (IWRM) is needed to manage water scarcity and ensure human well-being without compromising environmental sustainability [4]. The IWRM approach is the way forward for efficient, equitable and sustainable development and management of limited water resources and for coping with conflicting demands [5]. In the previous decades, traditional and innovative water harvesting techniques (WHTs) have gained more attention as one of the techniques of IWRM due to the limited alternatives for developing new water resources in arid and semi-arid areas [6]. WHTs consist of man-made systems to collect rainwater for beneficial uses or recharging the groundwater [7]. WHTs effectively reduce storm water runoff volumes [8], which can help tackle land degradation. The sustainability of WHT is essential to improve the well-being of rural populations due to their positive impact on water productivity under various socio-economic and environmental conditions [9]. Sustainability can be defined as the simultaneous pursuit of economic prosperity, environmental quality and social equity [10,11]. Pachpute et al. [12] define the sustainability of WHTs as the optimal long-term use of natural water resources able to address the concerns of livelihood-generation. Mainly three sets of attributes are used in literature to judge sustainability of WHTs: (i) agriculture productivity and income generation (ii) food security and social capital strengthening (iii) environmental conservation [12–16]. Several studies have attempted to evaluate sustainability of water resources systems using a sustainability index (SI) [17–20]. Reliability, resilience and vulnerability are the most commonly used criteria for evaluating SI.

Given the crucial role of WHTs for local stakeholders, it is striking that they are often not involved in the evaluation process. Several authors [21–23] have argued that stakeholder engagement is needed to guarantee the sustainability of WHTs. In the context of enhancing participation of stakeholders and dealing with sustainability assessment, multi-criteria analysis can be useful to evaluate a set of decision alternatives by stakeholders and to deal with conflicting goals [18,19]. On the other hand, an important challenge for operationalizing decision alternatives, on water management inter alia, is the question of how to consider spatial decision-making issues. Several studies [9,23–29] used only biophysical data to identify suitable areas for on-site and off-site WHT implementation. The most common input data are slope, rainfall, soil types and land cover [30]. Socio-economic data are rarely used [31–33]. Biophysical data are essential factors to identify suitable areas for WHT implementation, but using only biophysical data is not sufficient to perform a fully successful and sustainable water harvesting implementation [11,23]. Indeed, the integration of multi-criteria analysis with geographic information systems (GIS) could help users to spatially evaluate water management alternatives based on feasibility and a sustainability index. Considering both biophysical and sustainability criteria is essential for spatial modeling in water resource management, but has received little attention in most past studies. The novelty of this research lies in explicitly adding a sustainability index (SI) based on stakeholders' evaluations in identifying suitable locations for sustainable WHTs.

The Oum Zessar watershed, located in the southeast of Tunisia, is characterized by low, unpredictable and torrential rainfall and a negative water balance almost year round [34–36]. Currently Oum Zessar watershed provides blue and green water for rainfed agriculture as well as for both tourism and household needs. Since the mid-1980s, the Tunisian government has engaged in a vast program of soil conservation and water mobilization based on traditional knowledge and new techniques [36]. This investment concerned actions related to WHT implementation and maintenance. Two main categories of WHTs can be distinguished in Oum Zessar watershed based on the type of catchment and the size of WHT techniques: on-site and off-site WHTs. The on-site WHTs are small-scale practices usually implemented on privately owned cultivated areas to improve water retention and soil nutrients, and consequently to increase biomass production. Off-site WHTs are medium to large structures located in an uncultivated area, mainly for groundwater recharge and runoff spreading. The off-site WHTs are public property [37]. Currently, officers from the Regional Commissary for Agricultural Development (RCAD) are trying out to assess the effectiveness of the different categories of WHTs in relation to their location in terms of reliability of the water supply, water productivity and natural resource conservation. Evidence from the assessment of the program will serve to orient the planned WHT work to cover new areas of Oum Zessar watershed. Decision-makers demand a comprehensive and reliable ex ante and ex post assessment of WHT on sustainability [36,38]. In the watershed, in spite of the long history and rich traditional knowledge of implementing WHT, affected stakeholders have rarely been involved in catchment-level decision-making processes. This has led to low rates of adoption or failed adoption processes [34]. Therefore, close collaboration with stakeholders in the framework of an IWRM approach is needed to increase water management efficiency and evaluate the sustainability of WHT.

This study aims at identifying suitable sites for sustainable traditional and newly introduced WHTs in the Oum Zessar watershed. As stated above, we sought to address gaps in considering sustainability criteria and the integration of multiple stakeholders' perspectives in siting WHTs. A GIS-based multi-attribute rating technique, which combines feasibility criteria and a newly proposed stakeholder-defined sustainability index (SI), was used. The objective was twofold: (1) to promote stakeholder participation in decision-making concerning water resource management that enhances decision efficiency and improves acceptance of WHTs; and (2) to integrate sustainability criteria in the suitability maps for traditional and newly introduced WHTs. It is assumed that preferences of farmers and decision-makers in terms of the evaluation of the sustainability of traditional and innovative WHTs diverge, and that the approach taken can help reach better IWRM decisions. In the following sections, we first present the study area and our methodological approach (Section 2), with results and discussion following in Sections 3 and 4. Finally, conclusions are drawn in Section 5.

2. Materials and Methods

2.1. Study Area

The Oum Zessar watershed, located in the Medenine governorate in south-eastern Tunisia (Figure 1), covers 361 km^2 and has an arid Mediterranean climate characterized by low, erratic and torrential rainfall [36]. On average, the annual precipitation is about 157 mm. The coldest months are December, January and February with occasional freezing (down to −3 °C). June to August is the warmest period of the year and temperatures can reach as high as 48 °C [35]. Successive dry years, irregular rainfall and the occurrence of intensive storm events are considered the main physical causal factors of water shortage in the region. The Oum Zessar watershed has a strategic importance for water resource management given its geographical situation and its hydrological, ecological and socio-economic functions. The Zeuss-Koutine aquifer is the most important aquifer in the Oum Zessar watershed and provides water for human consumption, the agriculture sector and the growing tourism sector in the Medenine governorate, most notably on the isle of Djerba which itself has very limited groundwater resources [36,38]. The intensification of water and land use in the Oum Zessar watershed has led to soil fertility decline and water depletion. The increase in the exploitation of the Zeuss-Koutine aquifer has produced a continuous piezometric decline of 0.5 to 1 m year^{-1} on average between 1977–2014 [39]. The effects are less water being available for plant growth, lower biomass production and grain yield, and as a consequence less protection of soils by vegetation. In fact, 20% of the watershed is affected by soil erosion [40]. Based on the land surface elevation and administrative division, three geophysical zones can be distinguished in Oum Zessar watershed: (i) the upstream zone, covering the mountainous areas within the administrative territory of the Beni Khedache delegation; (ii) the midstream zone, starting from the border of the mountain zone and covering part of Beni Khedache and northern Medenine delegations and (iii) the downstream zone, starting from Koutine to the sea (Boughrara Golf), corresponding to the administrative territory of Sidi Makhlouf delegation. The Oum Zessar watershed is representative for the whole zone of south-east Tunisia and results of the case study can therefore be extrapolated to the wider area having comparable socioeconomic and biophysical characteristics (Figure 1).

2.2. Method

This section outlines the different steps of the modelling approach (Figure 2) used for the generation of a suitability map for potential sustainable WHTs [33,41,42].

Step 1: Identification of stakeholders
Step 2: Pre-selection of potential water harvesting techniques
Step 3: Calculation and interpolation of the sustainability index (SI)
Step 4: Identification of potential area based on biophysical criteria
Step 5: Generation of suitability maps; spatial integration of SI and biophysical layers

Step 1: Identification of stakeholders

Interaction with stakeholders starts first with identifying who the relevant stakeholders are [14,43,44]. Curșeu and Schruijer [45] pointed out the existence of two methods for stakeholder selection: (i) stakeholders can be identified through reputation, focus group or demographic analysis; and (ii) stakeholder selection can be an interactive approach where pre-selected stakeholders reveal other previously unknown stakeholders [46]. Taking into account the problem of the representation of selected groups and the difficulties in managing large numbers of stakeholders, we adopted an interactive approach for stakeholder selection. First, a discussion was held between scientists from the Institute of Arid Regions (IRA) and officers from the Regional Commissariat for Agricultural Development (RCAD) to identify who should be involved in the selection process as decision-makers interested in the Oum Zessar watershed. Secondly, scientists and decision-makers identified together a set of representative stakeholders affected directly by the implementation of WHTs in three compartments of the Oum Zessar watershed. To deal with the problem of representativeness and upscaling, we started by identifying a representative sub-catchment for each compartment of the watershed (up-, mid- and downstream). Four farmers from each sub-catchment were selected to participate within the framework of project workshops. The main selection criteria for participants was a strong background and knowledge about WHTs. In total, 24 stakeholders were targeted: (i) five scientists; (ii) five decision-makers; (iii) two representatives of NGOs; (iv) twelve farmers.

Step 2: Pre-selection of potential water harvesting alternatives and evaluation indicators with stakeholders

A multi-stakeholder learning process on the biophysical and socio-economic impact of water and soil conservation practices in the Oum Zessar study site was carried out in a workshop setting. The goal of the first workshop was to share understanding and a mutual learning on indigenous and innovative WHTs and to derive a range of WHT alternatives. Through interaction between technical experts and scientists, it was increasingly recognized that by combining traditional and innovative WHTs, more integrated water resource management could be established. A variety of techniques implemented during the last two decades was presented and discussed (Figure 3). Based on the World Overview of Conservation Approaches and Technologies (WOCAT) database, a set of innovative WHTs not yet implemented in the study area was also presented by scientists. The output of the first step was a set of potentially applicable indigenous and innovative techniques (Table 1).

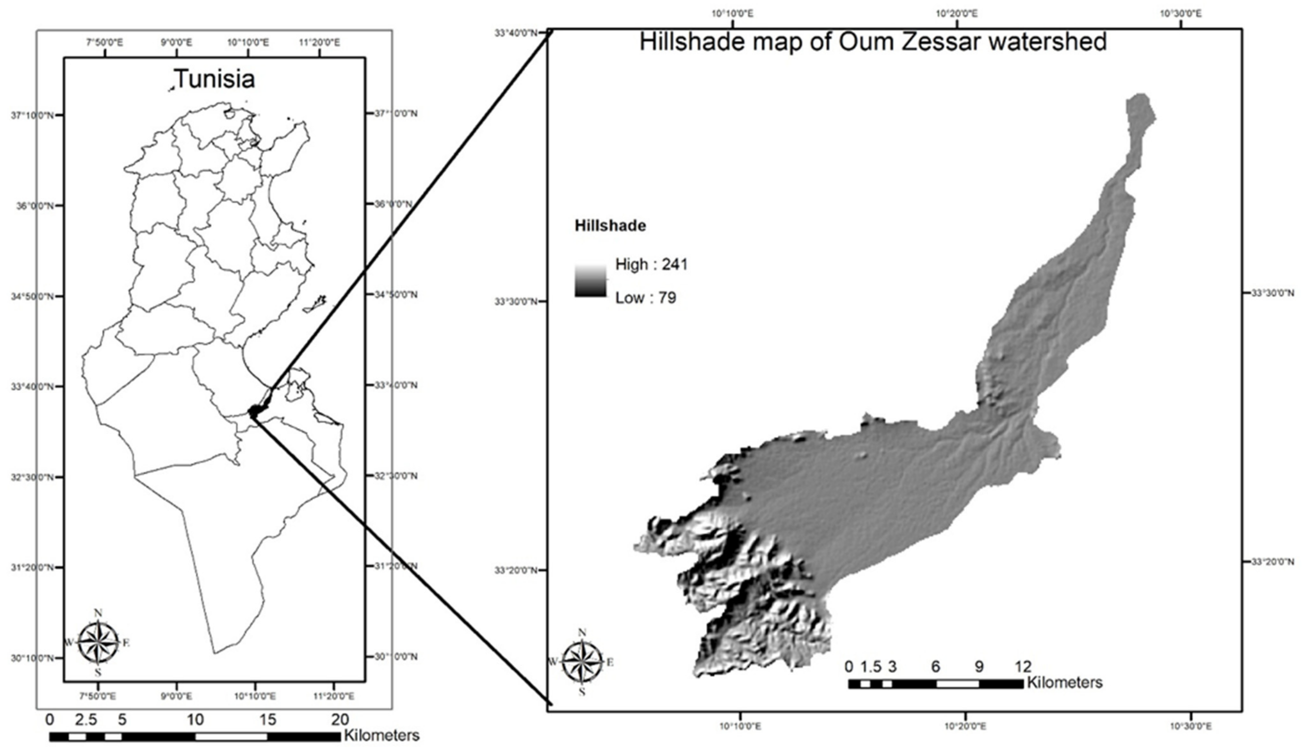

Figure 1. Geographical location of Oum Zessar watershed in Tunisia.

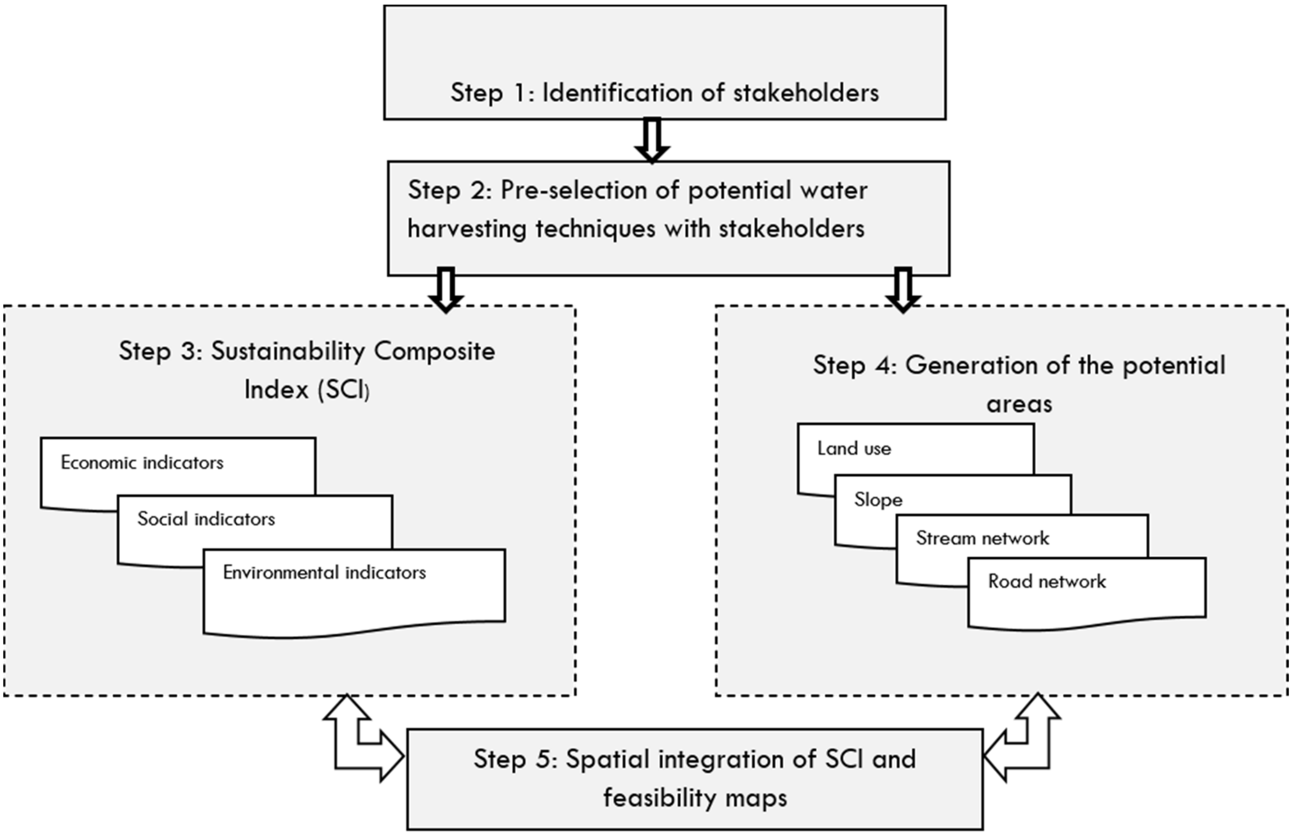

Figure 2. Hierarchical structure of the approach of selecting suitable WHT for each location in Oum Zessar watershed.

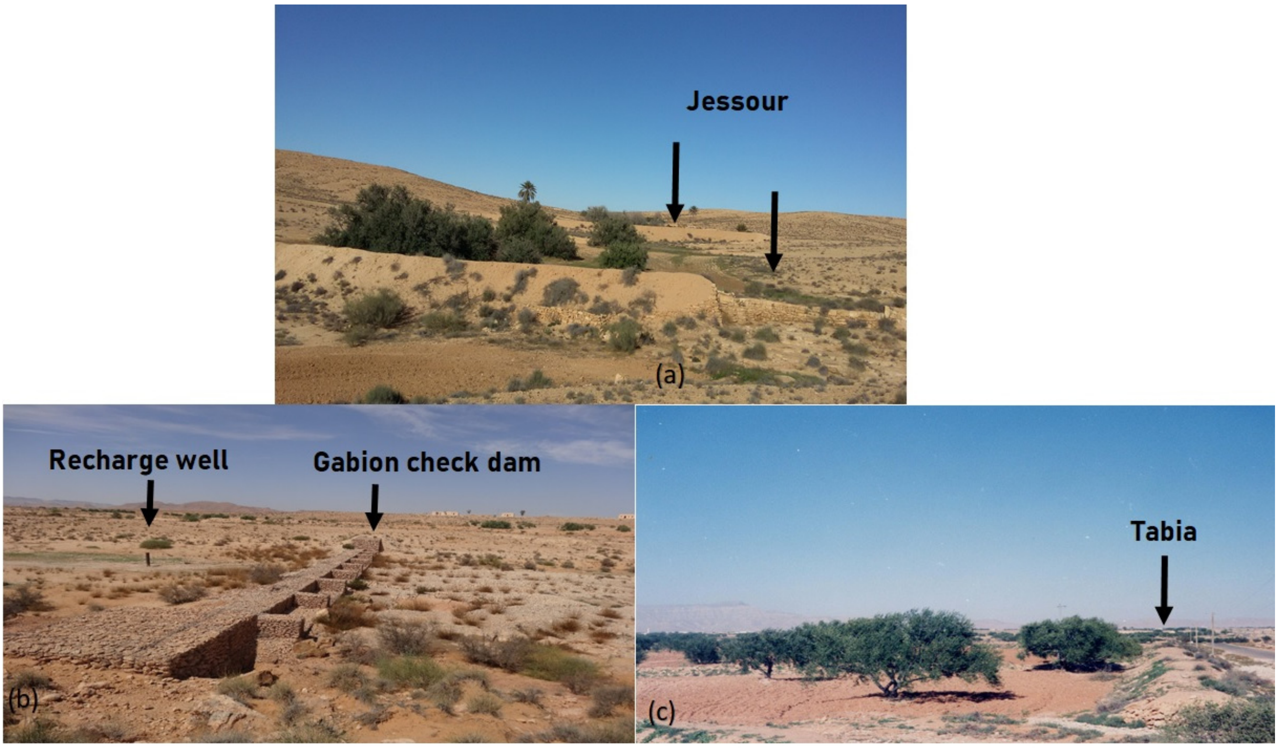

Figure 3. Jessour (**a**), gabion check dams (**b**) and tabias system (**c**) ((**a**–**c**) images by Mohamed Ouessar).

Table 1. Pre-selected water harvesting technologies (alternatives).

Techniques	Origin	Definition/Comments
Jessour	Indigenous	Jessour (plural of jesr) is an ancient runoff water harvesting technique widely practiced in the arid highlands in Tunisia (WOCAT Database). It consists of small dams built across wadis and gullies to intercept rainwater and sediments. A jesr is composed of three main components: a dike in the form of a small earth embankment with a spillway made of stones, a terrace that represents the cropping area and an impluvium [47,48]. (see Figure 3)
Tabias	Indigenous	The tabia earthen dyke is a water harvesting technique used in the foothill and piedmont areas. (WOCAT Database). Tabias (plural of tabia) are hydraulic units situated in the middle of a catchment on moderate slopes. A tabia is formed by an embankment along the contour with lateral bunds. It collects water from an impluvium or by the diversion of wadi runoff [48]. (see Figure 3)
Cisterns	Indigenous	Cisterns are reservoirs used for storing rainfall and runoff water for multiple purposes: drinking, animal watering and supplemental irrigation (WOCAT database).
Recharge wells	Indigenous	A recharge well comprises a drilled hole up to 30–40 m deep that reaches the water table, and a surrounding filter used to allow the direct injection of floodwater into the aquifer (WOCAT database). (see Figure 3)
Gabion check dams	Indigenous	The technology of a check dam is a technique consisting of binding different gabion cages filled with small stones together to form a complete flexible gabion unit (WOCAT database). (see Figure 3)
Zai planting holes	Introduced (Burkina Faso)	Zai is an ancestral planting pit developed in the Yatenga province, north-western Burkina Faso, where average rainfall is about 600 mm, with recurrent droughts and where soils are heavily encrusted [49].
Retention ditches	Introduced (Ethiopia)	Retention ditches, also called infiltration ditches, are larger ditches designed to catch and retain all incoming runoff for infiltration into the soil [50].

Step 3: Calculation of WHTs Sustainability Index (SI)

Sustainability is a complex and multidimensional concept. Numerous indicators and indices are used to evaluate sustainability [47]. The use of a composite index is useful to enable policy monitoring, public communication and the generation of rankings [10,51,52]. However, even if an index is simple to understand and analyze, it is difficult to formulate. SI represents an aggregate measure of a combination of performance measures, or in other words, an index is a "*synthesis of numerous factors into one given factor*" [48–50]. Its construction requires "*several choices, namely the selection of variables, methods of aggregation, normalization, and weighting to apply*" [53].

During a second workshop, a list of balanced indicators for evaluating economic, social and environmental sustainability of each WHT was compiled and discussed in depth together with participants. A common agreement and understanding of indicators was sought in a plenary session. Each sustainability pillar (social, economic and environmental) was translated into three indicators (Figure 4). Afterwards, two breakout groups of stakeholders were formed: famers and decision-makers. The former was composed of 12 farmers and the latter was composed of 8 decision-makers. Stakeholders were asked to score the anticipated impacts of WHTs on each indicator in the three watershed locations (upstream, midstream and downstream) using the following scoring range: 0 = no impact up to 10 = extremely high impact. Furthermore, stakeholders were asked to assign weights to the level of importance of each sustainability pillar and indicators reflecting their individual preferences. A 0–10 scale was used to weigh sustainability pillars and indicators, where 0 indicates low importance and 10 indicates high importance. The given weights translate into individual preferences for each sustainability pillar. Different weights and scores are subsequently used to quantify the SI of each WHT alternative. The Simple Multi-Attribute Rating Technique (SMART) developed by Edwards (1977) seems to be the most comprehensive and easy to use [53]. The SMART method is preferable to evaluate single alternatives in isolation [51] and to communicate easily with stakeholders [52]. It seeks to validate and quantify the user's preference, usually on a scale 0–1, 0–10 or 0–100. The single weighted value represents in our case study the sustainability index (SI) for each alternative WHT.

$$\mathrm{SI}(a\ i) = \sum_{i=1}^{m} w_i a_{ij} / \sum_{i=1}^{m} w_i \ \ j = 1, \ldots.., n \tag{1}$$

where, for each *i* alternative, SI is measured as the weighted sum of performances a_{ij} for this alternative on each of the *j* indicators, weighted by their relative importance, w_i reflecting its importance.

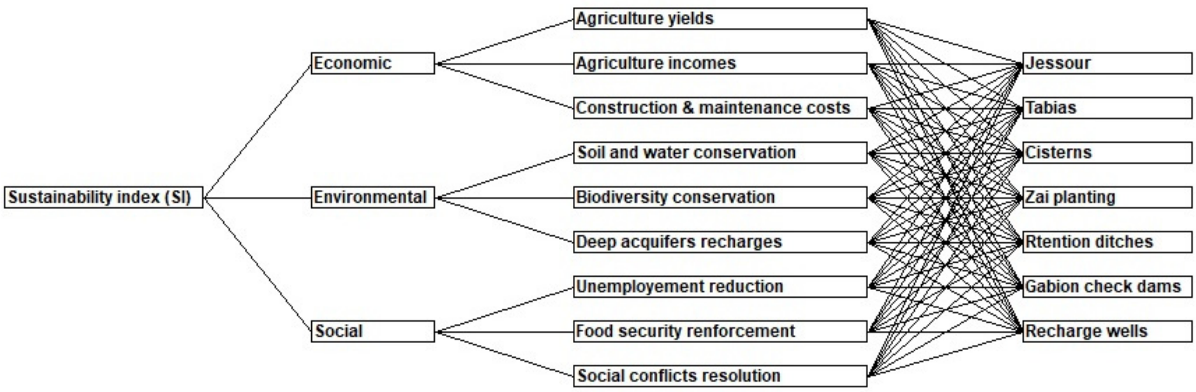

Figure 4. Tree of sustainability index, sub-criteria, criteria and WHT alternatives.

The SI was calculated for each water harvesting technique, for each group of stakeholders and for each location (up-, mid- and downstream) (for an example see Table 2). A geostatistical tool, kriging, was used in ArcGIS to interpolate measured values of SI. The SI layer allows WHTs to be ranked on sustainability on a scale from 0–10.

Table 2. Overall SI of jessour techniques in upstream area performed by decision-makers.

Sustainability Dimensions	Weight (1)	Criteria	Weight (2)	Overall Weight (1 × 2)	Average Score (3)	SCI (1 × 2 × 3)
Economic	0.333	Construction and maintenance costs	0.262	0.087	0.60	0.0523
		Agriculture yields	0.308	0.103	0.65	0.0667
		Agriculture incomes	0.431	0.144	0.65	0.0933
Environmental	0.356	Soil and water conservation	0.362	0.129	0.80	0.1031
		Biodiversity conservation	0.298	0.106	0.80	0.0849
		Deep aquifer recharge	0.340	0.121	0.35	0.0424
Social	0.311	Unemployment reduction	0.418	0.130	0.55	0.0715
		Food security reinforcement	0.328	0.102	0.65	0.0663
		Social conflicts resolution	0.254	0.079	0.70	0.0553
Total	1			1		0.6357

Step 4: Identification of potential area based on biophysical criteria

Criteria for the identification of a potential site were selected based on criteria used frequently in previous studies (54–60) and with respect to the experts' knowledge and experience in the area. Accordingly, slope, land use, distance to road and distance to wadis were selected as thematic layers. Biophysical layers were classified and combined using the Raster calculator tool in the Spatial Analyst module of ArcGIS 10.1 software. Data were gathered from the Laboratory of Eremology and Combating Desertification (LECD, IRA) at 1:250,000 scale on the watershed border, districts and villages, hydro-geophysical zones, land use, roads and wadis and a DEM that were used to prepare maps for the biophysical criteria (Figure 5). The parameters listed in Table 3 were used to classify pixel values from 0 to 10. The scores reported were discussed and adjusted together with technical experts from IRA and CRDA. The most suitable areas were classified as 10, while the least suitable were classified as 0.

Table 3. Ratings and scoring for each suitability criteria and each WHT.

Parameters	Ratings	Score							References
		Jessour	Tabias	Cisterns	Zai	Retention Ditches	Recharge Wells	Gabion Check Dams	
Slope (%)	<5	4	8	4	8	8	6	6	[54–56]
	≥5, <15	8	6	6	4	4	8	8	
	≥15, <20	6	4	8	0	0	2	2	
	≥20	2	0	6	0	0	0	0	
Land use	Cereals	8	10	4	6	4	2	6	[54,55]
	Sand	2	2	0	0	0	0	0	
	Halophytes	2	2	0	0	2	0	0	
	Olive	10	10	6	4	8	6	8	
	Rangelands	6	8	8	4	6	6	4	
	Rocks	0	0	4	0	0	0	0	
	Bare soil	0	2	0	0	0	0	0	
Distance to wadis (m)	<5000	8	8	8	4	4	10	10	[57,58]
	≥5000, <10,000	6	6	6	2	6	8	8	
	≥10,000, <15,000	4	4	4	0	4	6	6	
	≥15,000	2	2	2	0	2	4	4	
Distance to road (m)	<5000	8	8	0	0	0	8	10	[58–60]
	≥5000, <10,000	4	4	0	0	0	6	8	
	≥10,000, <15,000	6	6	0	0	0	4	6	
	≥15,000	2	2	0	0	0	2	2	

Source: Scores are based on face-to-face scoring session together with scientists and stakeholders.

Step 5: Generation of the suitability maps of sustainable WHT

SI measures of different WHTs (Step 3) were reclassified and interpolated for each location in the study site. Consequently, scaled maps between 0 and 10 were obtained so that pixels with a value 0 represent locations with low sustainability of WHTs, while a value of 10 represents locations with a high sustainability level. Finally, the biophysical (Step 4) and sustainability index layers were combined using a raster calculator (Figure 6). The suitability values which are obtained are classified into four classes: unsuitable (0–15), marginally suitable (15–25), suitable (25–35) and very suitable (35–50).

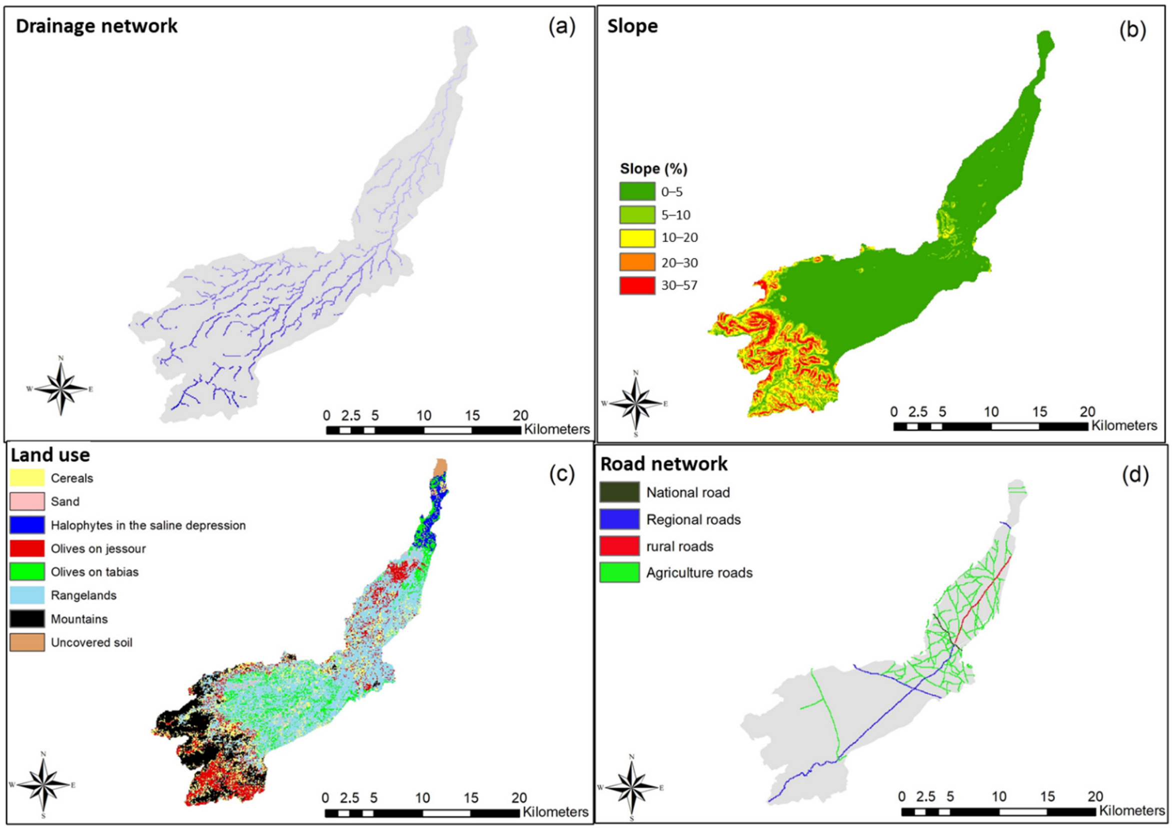

Figure 5. Maps of drainage network (**a**), slope (**b**), land use (**c**) and roads (**d**) in the study area.

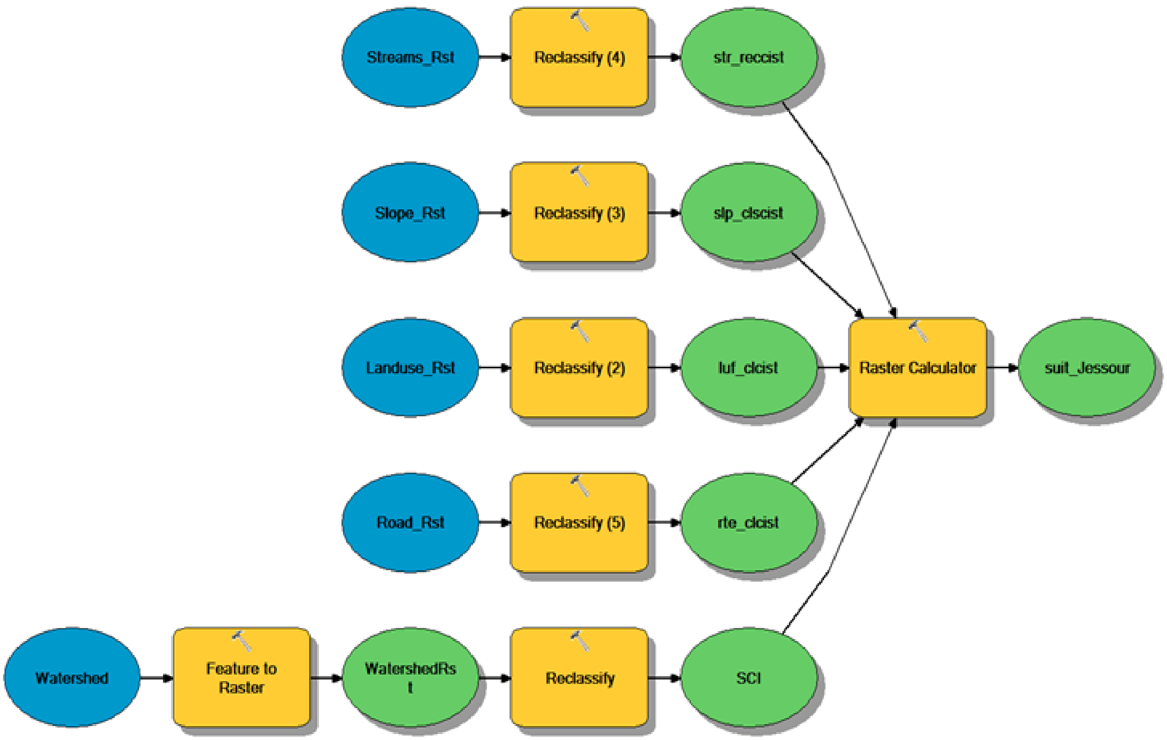

Figure 6. Flow chart for the identification of potential RWH sites.

3. Results

3.1. Sustainability of WHTs

Twelve farmers and eight decision-makers participated in the weighting and scoring session of different WHTs in up-, mid- and downstream parts of the watershed. Figure 7 depicts the SI of all WHTs for both farmers and decision-makers. For farmers, the most sustainable techniques were jessour and tabias upstream (0.59), recharge wells midstream (0.77) and, interestingly, retention ditches downstream (0.58). In the upstream catchment, farmers valued the sustainability of traditional techniques highest while introduced techniques, such as retention ditches and zai planting, are the least appreciated. In the upstream area, jessour promote agricultural yields (0.11) and incomes (0.08), soil and water conservation (0.09) and biodiversity (0.08). To some extent, in the midstream catchment recharge wells promote agricultural income (0.12) and unemployment reduction (0.14). This can be explained by the use of groundwater resources for irrigated agriculture, which is practiced mostly in this part of Oum Zessar watershed. As reported by farmers, retention ditches in the downstream catchment might reinforce food security (0.1) and increase agricultural yields (0.08) and incomes (0.08). The high score given to retention ditches shows the acceptance by local farmers of this new WHT technique based on the sharing of lessons learned from other countries.

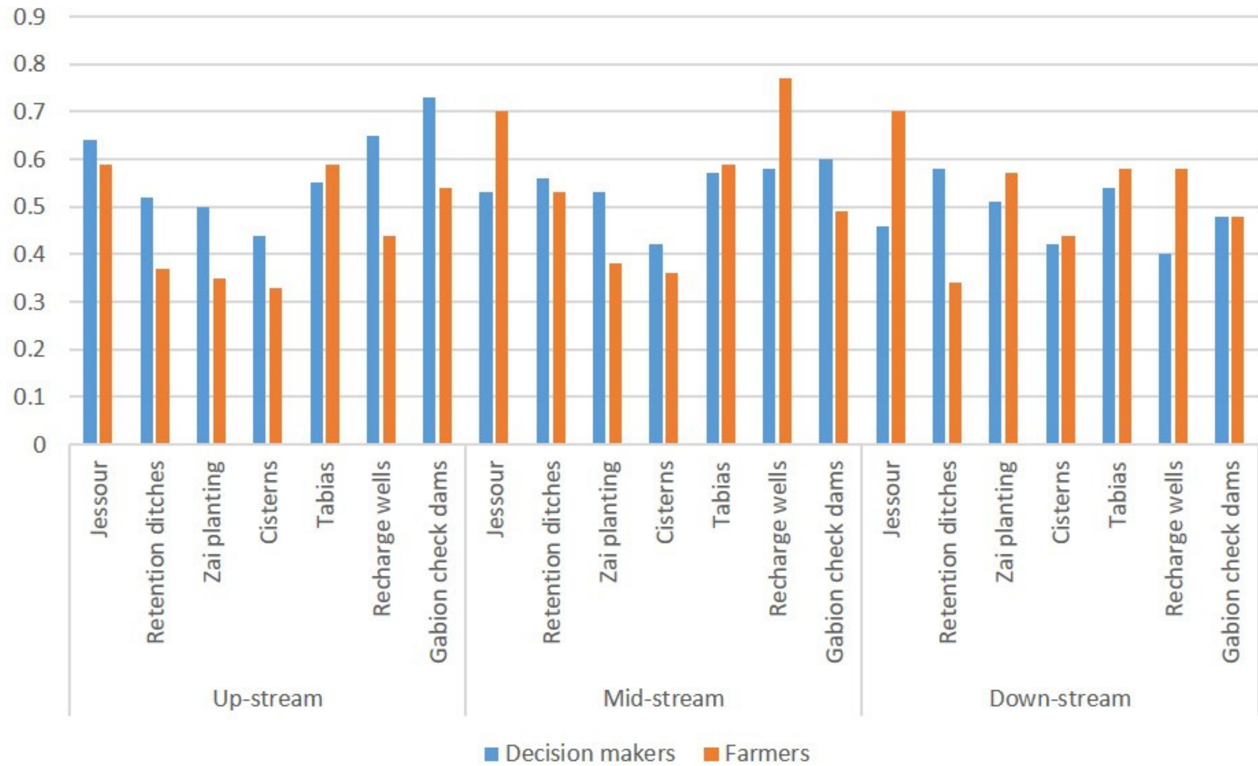

Figure 7. SI results for each WHT for both farmers and decision-makers in up-, mid- and downstream parts of the watershed.

For decision-makers, gabion check dams and recharge wells are the most promising techniques in the upstream and midstream with scores of 0.73 and 0.65 in upstream and 0.60 and 0.58 in midstream zones, respectively. Recharge wells are usually used in combination with gabion check dams to enhance the infiltration of floodwater into the aquifer. As expected, the results show that decision-makers are more interested in large structures, applicable at large scale. A notable convergence between farmers and decision-makers was found in the downstream part of the watershed. As for farmers, retention ditches were highly prioritized by decision-makers (0.58).

Sustainability performances of the three dimensions are slightly different (Figure 8). Social sustainability presented the best performance among the three dimensions (the contribution of social sustainability in the SI accounts for approximately 40%), followed by economic sustainability (the contribution of economic sustainability in the SI accounts for approximately 33%) and environmental sustainability (the contribution of environmental sustainability in the SI accounts for approximately 28%). Sustainability evaluations of farmers and decision-makers largely align. Subtle divergences between the sustainability performances of the three dimensions and convergences between the sustainability evaluation of farmers and decision-makers can be explained as follows. Farmers value social sustainability based on their own need to reduce the unemployment rate and reinforce food security. The contribution of the environmental dimension to the SI was the lowest for farmers and decision-makers in the different locations. In fact, the Tunisian revolution (14 January 2011) initiated a change in the socio-political and economic systems that created the need to re-think and adapt existing development strategies. Income disparity was assumed by stakeholders to increase, leading to higher poverty rates and social issues.

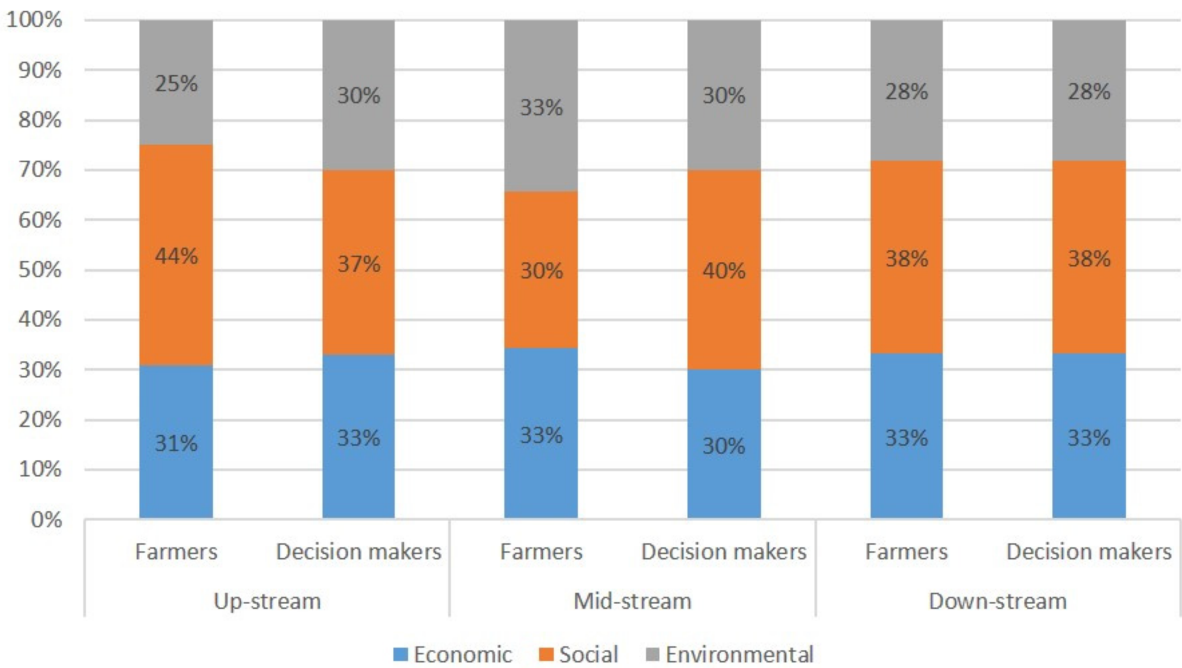

Figure 8. Contribution of each sustainability dimension to SI according to farmers and decision-makers in up-, mid- and downstream parts of the watershed.

3.2. Suitable Sites for WHTs

Overall, it was found that the calculated minimum value of suitability was 8 and the maximum was 45. Differences in suitable area are attributed on the one hand to the importance of spatial variability in parameters for identifying potential sites for WHTs including slope, land use, distance to wadis and distance to road (Figure 5) and on the other hand to the SI (Figure 8). Areas which have a high value of suitability are supposed to be biophysically suitable for implementing a specific sustainable WHT in terms of (i) reliable water supply and production potential, (ii) effectiveness of water use and (iii) minimal negative impacts on natural resources.

After overlaying each biophysical criterion map on the SI maps, we obtained the following results (Figures 9 and 10). In the 361 km^2 area of the study site, according to farmers 256 km^2 (71%) is suitable and 101 km^2 (28%) is marginally suitable for the jessour technique. In contrast, for decision-makers only 27% of the total area is suitable to implement the jessour technique. Sites suitable for jessour occur predominantly in the mountainous regions of the catchment. For farmers, 292 km^2 (81%) of the total area is very suitable for tabias. For decision-makers, only about 144 km^2 (40%) of the total watershed is very suitable for the tabias technique. Tabias are located mainly on the foothills and piedmont areas of the catchment. Farmers and decision-makers agree that the introduced WHTs such as retention ditches and zai could be a promising technique within the watershed. Respectively, around 271 km^2 and 293 km^2 out of the total area is suitable for retention ditches and zai techniques and both farmers and decision-makers found 5% of the total watershed area to be very suitable for retention ditches. Retention ditches and zai techniques are suitable mainly on the gentle slopes in the midstream and downstream areas. Overall, the most suitable techniques for farmers are tabias and gabion check dams, with a percentage of very suitable area of 81% and 75%, respectively. For decision-makers, gabion check dams seem to be the most suitable technique and can be implemented within 293 km^2. The most suitable sites for gabion check dams are located close to the main river and have moderately undulated slopes.

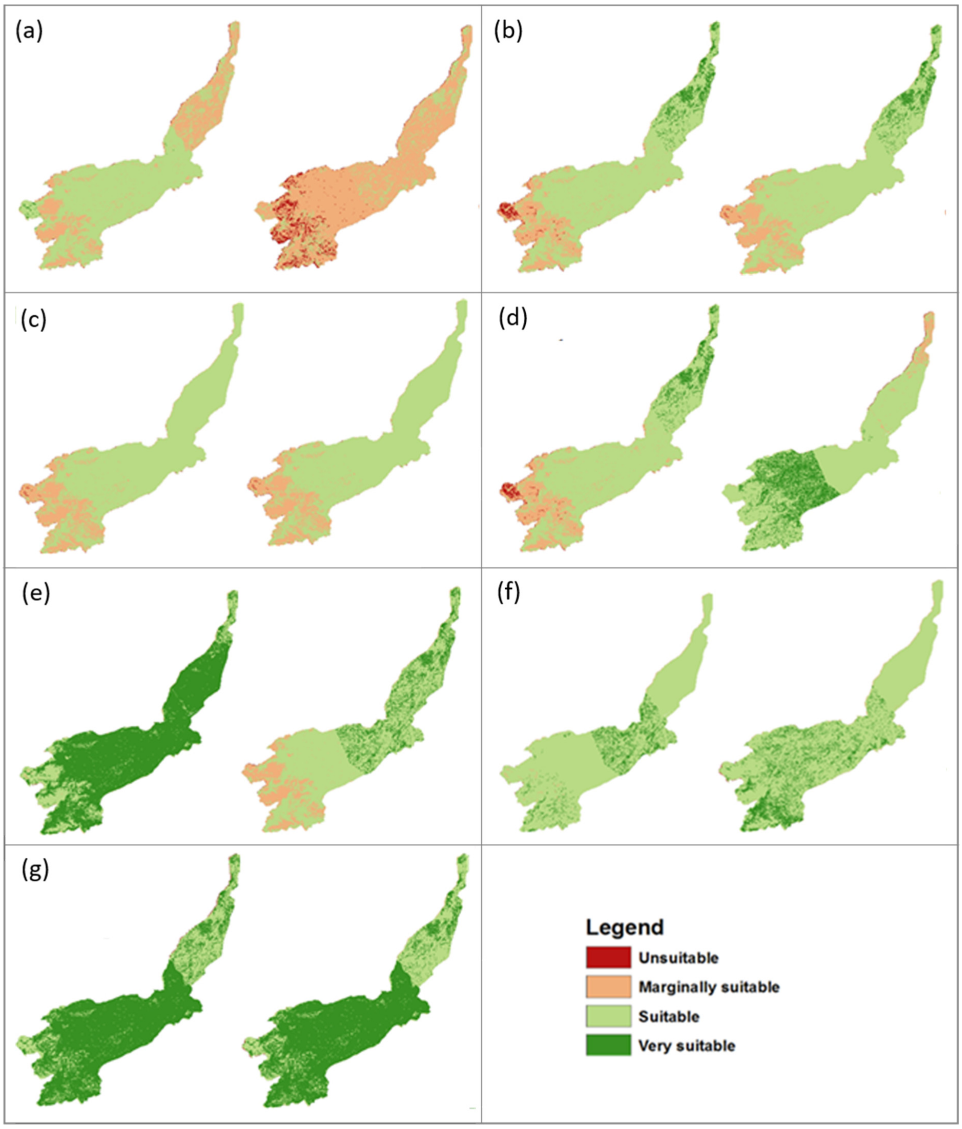

Figure 9. Suitability maps of Jessour (**a**), Retention ditches (**b**), Zai planting (**c**), Cisterns (**d**), Tabias (**e**), Recharge wells (**f**), Gabion check dams (**g**). In each panel left suitability according to farmers, right according to decision-makers.

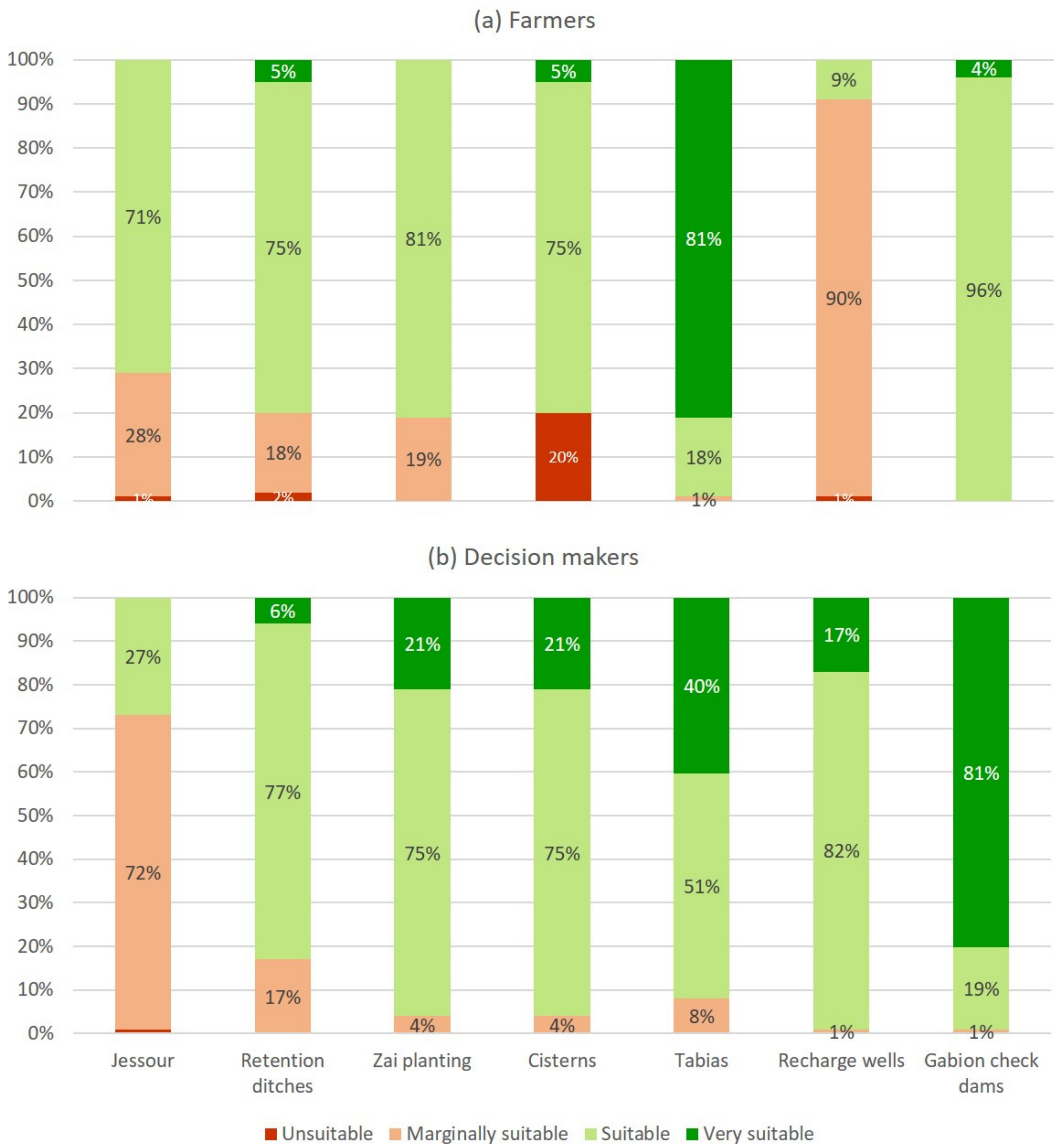

Figure 10. Percentage of Oum Zessar catchment area suitable for WHT implementation as rated by (**a**) farmers and (**b**) decision-makers.

Using the highest position tool in GIS-spatial analysis tools, the technique with the highest suitability value in each cell was selected. Figure 11 and Table 4 show results for farmers and decision-makers' rankings, respectively. For farmers, jessour, tabias, gabion check dams and recharge wells are the most suitable and sustainable techniques within the watershed. Tabias represent the highest-scoring WHT in more than 75% of the total watershed, while gabion check dams occupied around 25% of total area. For decision-makers, almost 80% of the total area is considered most suitable for gabion check dams, and 2.3% of the watershed could be suitable for retention ditches.

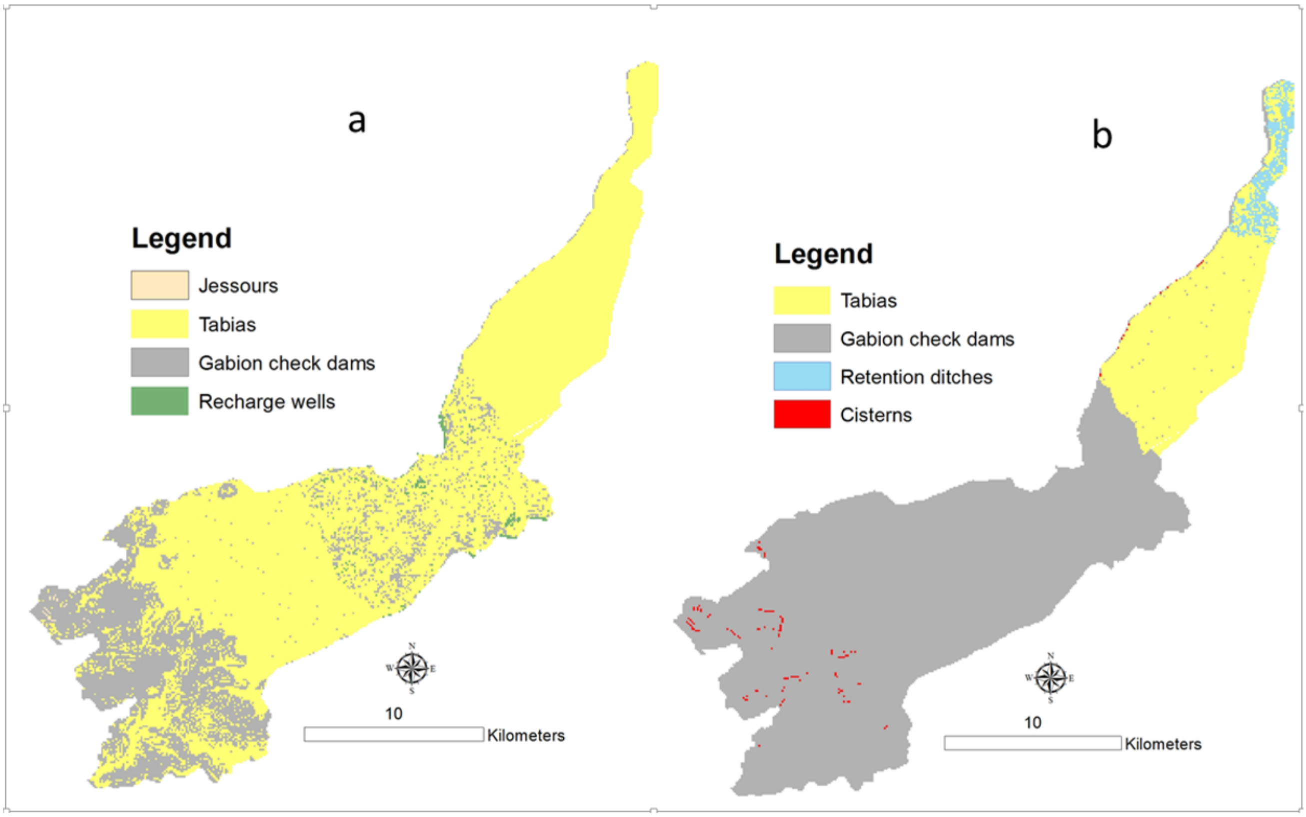

Figure 11. WHT with the highest suitability values in each cell for farmers (**a**) and decision-makers (**b**).

Table 4. WHT with the highest suitability values for farmers (a) and decision-makers (b).

Stakeholders	Techniques	Percentage (%)	Area (km^2)
Decision-makers	Tabias	19.3	69.71
	Gabion check dams	78.1	282.13
	Retention ditches	2.3	8.22
	Cisterns	0.3	1.26
Farmers	Jessour	0.1	0.25
	Tabias	75.4	272.28
	Gabion check dams	23.8	86.00
	Recharge well	0.8	2.78
Total area (km^2)			361.32

4. Discussion

As explained and illustrated above, our approach allows the generation of suitability maps for each of a series of traditional and innovative water harvesting techniques in a semi-arid region. It thereby considers both biophysical limitations (slope, land use, distance to road and distance to stream) and sustainability criteria. Sustainability criteria are integrated as a composite index of social, economic and environmental domains. This adds an additional explicit variable compared to similar approaches to deal with suitability analysis documented in the literature, e.g., by Grum et al. [33], Pachpute et al. [12] and Mechlia et al. [61], for combining socio-economic and biophysical factors to generate WHT suitability maps. These studies differ in how they consider interaction between WHTs and socio-economic factors and how they interpret outputs: whereas previous studies evaluated the impact of a set of biophysical (rainfall variability and runoff quality and quantity) and socio-economic (local skills and investment capacity, labor availability and institutional support, etc.) criteria to identify potential sites of water harvesting, our approach accommodates both types of assessment approaches, and tries to explicitly integrate a sustainability measure, not only to assess WHTs' impacts but in addition to generate WHTs' suitability maps.

Suitability maps of innovative and traditional WHTs generated in the case study were scaled up from participatory modelling outputs, and are therefore inherently difficult to validate. An existing map of WHTs provided by the LECD, IRA in the Oum Zessar watershed can be used to test the performance of our methodology (Figure 12). We followed a simple strategy for the validation. We assessed the reliability of results by comparing the generated maps with existing WHTs locations. Nevertheless, this is far less straightforward when considering innovative techniques such as zai and retention ditches that have not yet been implemented in the catchment. The main existing WHTs in Oum Zessar watershed are jessour on the mountain ranges, tabias and cisterns on the foothills and piedmont areas and gabion check dams and recharge wells in the wadis. Compared to the already existing WHTs in the study site, the applied methods showed consistent results. The area identified as very suitable or suitable for jessour, tabias, cisterns, check dams and recharge wells by farmers and decision-makers were mostly located in the same areas where they occur in reality. The fact that most traditional water harvesting techniques were found within the very suitable and suitable classes indicates that our approach can be used to predict potential sites for rainwater harvesting techniques.

Numerous modelling tools and methods that have previously been used to evaluate WHTs focused on long-term simulations of WHT monetary profits [1]. However, few of those modelling tools and methods paid attention to farmers' awareness of environmental and societal concerns. These results illustrate that farmers recognized more than just financial gains from WHTs. Adequate incorporation of these concerns into choices of the suitable location of WHTs will enlarge the scope for more inclusive and sustainable solutions to water management issues [14]. Based on these results, a combined system of both traditional and innovative WHTs taking into account economic, environmental and social aspects can be an alternative for the watershed management, appreciated by the local communities.

Furthermore, we noticed a high level of agreement between stakeholders (12 farmers or 8 decision-makers) in terms of sustainability assessment. Indeed, an exchange of arguments and an open discussion between different groups as a follow up to the first scoring session lead to adjustments of the final choices and establishment of a common agreement between and within groups of involved stakeholders. Consequently, this gives an indication that further increasing the number of respondents will likely not lead to different results.

Participants were engaged in the IWRM process to support sustainable development based on WHTs. Participants highlighted the advantage of the participatory approach used to integrate environmental, economic and social issues and to ensure the transparency and the adaptiveness of the modelling process as tools for decision-making. However, they expressed the need for additional spatially explicit information, such as upstream/downstream outflow and interaction between surface water and groundwater, in order to develop a realistic local water management plan. Furthermore, they argued the need for more research to translate qualitative into quantitative information in order to facilitate impact assessments of WHTs on sustainability.

The collaboration between scientists, actors and decision-makers requires the establishment of a platform to discuss environmental problems and present the needs of the local population. We postulate that such a participatory approach will lead to a better adoption rate of innovative and traditional WHTs, and higher engagement during the process. Similar suggestions are also reported in the literature, e.g., ref. [14,15,62].

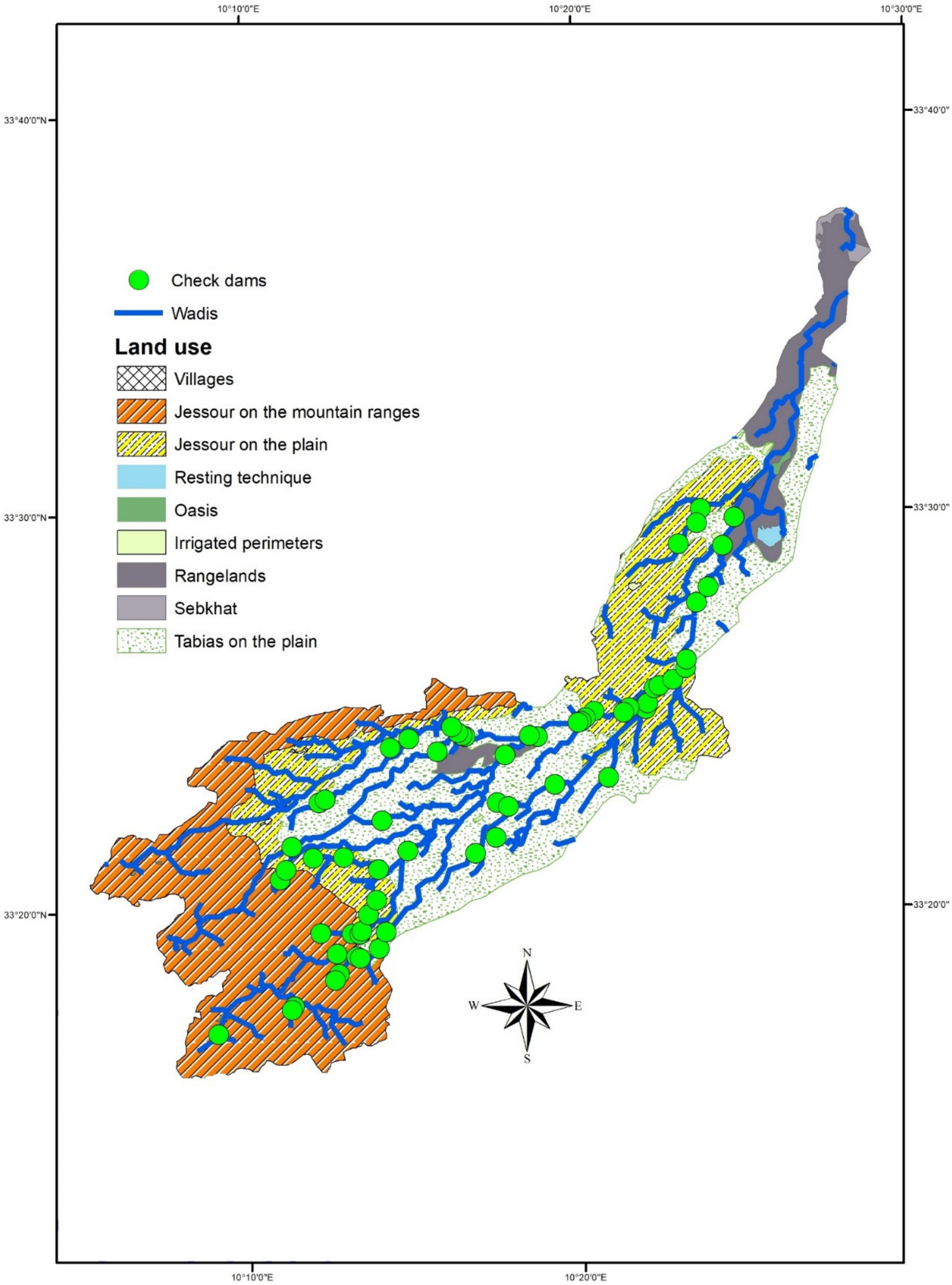

Figure 12. Existing water harvesting techniques in the Oum Zessar watershed.

5. Conclusions

Water harvesting techniques are promising techniques to deal with water scarcity in arid and semi-arid regions. WHTs could be a component of an integrated land and water management strategy to cope with climate change and to promote social, economic and environmental sustainability. Nonetheless, engaging stakeholders in the identification of suitable areas while integrating a sustainability assessment remains a challenging task. This study adds to the existing literature on water resource planning by defining and integrating a sustainability index evaluated by stakeholders to generate WHT suitability maps. The main findings of this study are as follows:

First, the results showed that farmers are more attached to the traditional small-scale WHTs and paid little attention to innovative techniques while decision-makers are more interested in large structures, applicable at large scale. This requires decision-makers to carefully reconsider the merits of traditional WHTs and to integrate and disseminate among farmers the knowledge and practices derived from trans/interdisciplinary approaches to facilitate, share and upscale good practice in water harvesting.

Second, the results illustrate that farmers recognized the social and environmental importance of WHTs, aside from just financial gains, resembling policy makers' sustainability considerations more closely than anticipated. Indeed, future investigation can incorporate such sustainability criteria into modelling approaches to enlarge the scope for more inclusive and sustainable solutions to water management issues.

Third, conducting a participatory approach that involves farmers and policy makers to identify suitability maps for WHTs is important for enhancing transparency of the planning process and improving acceptance and fuller implementation of the selected WHTs. Participatory approaches are deemed essential for enhancing collaboration and can also lead to the establishment of social networks for water management at the local level.

Overall, this study demonstrated that the combination of a multi-attribute decision making approach and GIS tools offers a powerful tool to identify the most sustainable water harvesting techniques and the most suitable areas for their implementation. Suitability maps are useful for decision-makers for efficient planning to ensure sustainable water supply for agricultural uses and to recharge the aquifers used for drinking water and for the tourism sector. Future improvements could involve an option to include more spatial data layers on stakeholder-prioritized criteria and monitoring of implemented WHTs, especially innovative ones, to evaluate their sustainability. Since the methodology and the analyses demonstrated in this study have generic applicability, they are also very useful for other parts of the world, particularly for arid and semi-arid regions.

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