GIS-Based Entropy–TOPSIS Ranking of Centralized Rainwater Harvesting Sites Using DEM-Derived Hydrological Indices: Karbala Province, Iraq

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Abstract: Water shortage has been a significant issue in arid and semi-arid areas owing to the uneven rainfall distribution, population explosion, and mounting pressure on the traditional water resources. Centralized rainwater harvesting (RWH) systems represent a technically feasible and sustainable approach for augmenting water resources; however, their effectiveness largely depends on the careful selection of suitable locations. Accordingly, this study proposes a GIS-driven decision-support model that integrates DEM-derived hydrological indices with an objective multi-criteria decision-making (MCDM) framework to identify suitable sites for the implementation of centralized RWH systems in Karbala Province, Iraq. Based on Shuttle Radar Topography Mission (SRTM) data, and spatial analysis, six physically meaningful criteria were obtained, namely mean slope, mean elevation, mean curvature, mean log-transformed flow accumulation, mean distance to streams, and site area. To reduce subjectivity, the Entropy Weight Method (EWM) was used to find the relative significance of each criterion objectively. Technique of Order of Preference by Similarity to an Ideal Solution (TOPSIS) was used to rank 23 candidate sites according to their proximity to the ideal solution. The findings indicate that site area and flow accumulation account for the largest share of influence on site suitability, whereas elevation and curvature contribute a comparatively smaller proportion to the overall assessment.

Keywords: Rainwater harvesting, GIS, Entropy weight method, TOPSIS, DEM hydrology, Karbala Province, Iraq

1. Introduction

Water shortage has become one of the most urgent environmental issues in the world specifically the arid and semi-arid areas where rainfall is scarce and very

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inconsistent [1], . Water stress has been a major problem in most developing nations such as Iraq due to the rapid growth of population, climatic change, and overuse of surface and groundwater[2,3] .

Rainwater harvesting (RWH) is widely recognized as an effective alternative water resource that can alleviate pressure on conventional water supplies by capturing and storing surface runoff for later use [4,5]. However, the performance of centralized RWH systems is strongly governed by appropriate site selection, as geomorphological and hydrological characteristics control both runoff generation and its retention potential [6,7]. In this regard, Geographic Information Systems (GIS), when coupled with multi-criteria decision-making (MCDM) techniques, offer a robust and systematic framework for the spatial evaluation and ranking of suitable RWH sites [8,9].

Nevertheless, subjective weighting methods like AHP can lead to bias and decrease the reproducibility, and objective weighting algorithms should be used ([10]; 11].This study aims to overcome subjectivity in centralized rainwater harvesting site selection by developing an objective GIS-based decision-support framework. Criterion importance is derived from data variability using entropy-based weighting, and candidate sites are ranked according to their proximity to ideal solutions through TOPSIS. The framework is applied to Karbala Province, Iraq, using DEM-derived hydrological indices to support practical site-selection decisions.

2. Materials and Methods

2.1 Study Area

Karbala Province is located in central-western Iraq, southwest of Baghdad, between latitudes 32.3deg-32.7deg N and longitudes 43.8deg- 44.2deg E, covering approximately 5,034 km^2. The region is characterized by flat alluvial plains in the eastern part and plateaus with low hills in the western part[12]. Most of the province belongs to the Mesopotamian alluvial plain, with gentle slopes and predominantly clayey to silty soils, which are favorable for surface runoff accumulation [13].

Geologically, Karbala lies within Quaternary sedimentary formations composed mainly of clay, silt, and sand, with localized limestone and sandstone exposures toward the western margin near the Anbar Plateau. These geological and topographical characteristics play a crucial role in determining surface hydrology and the region's response to climatic stresses such as drought and desertification [14].

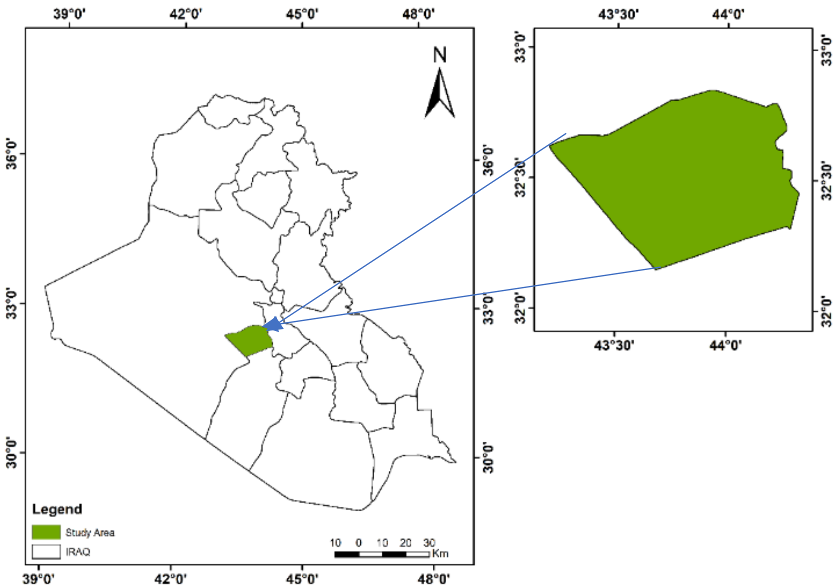

Figure 1: Location Map of the Study Area

2.2 Data and Criteria Selection

2.2.1 Data Sources

The main data in the form of the terrain and hydrological analysis was the 30 m Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) Figure 2, Table 1. The DEM is a measure of elevation values in about 1 arc-second (about 30 m), which is appropriate to hydrological screening of catchments in data-poor areas. [15]. All space processing was done in ArcGIS, and it involved conditioning of DEM and hydrology derivation. The Hydrology toolset was used to create flow direction and flow accumulation and the drainage (stream) network was extracted based on a specified threshold of the accumulation grid. [16].

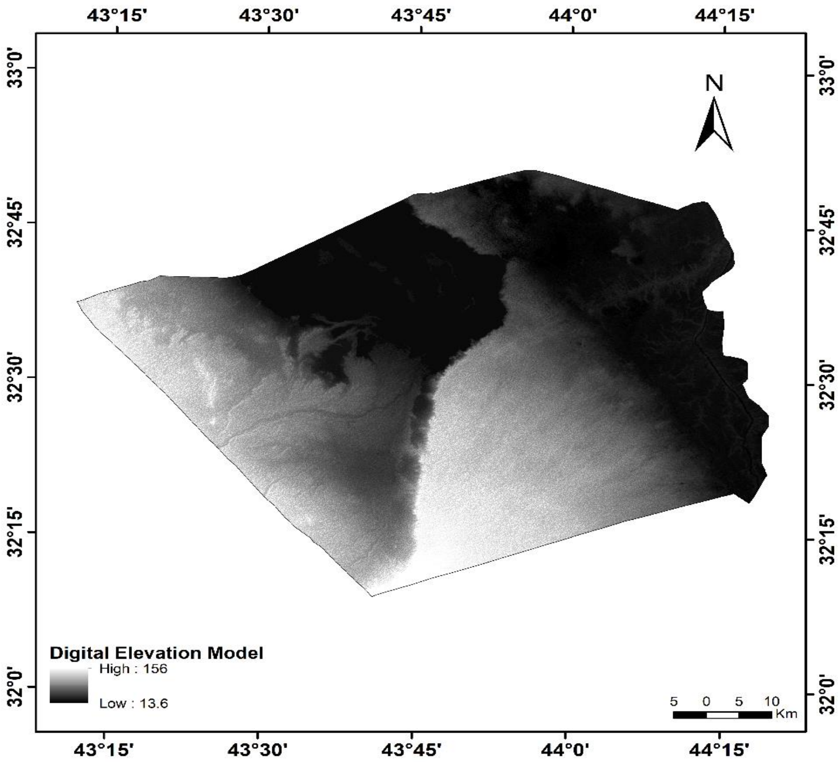

Figure 2: Digital Elevation Model (DEM) of the Study Area

For each candidate polygon, mean values of DEM-derived criteria were extracted using zonal statistics (mean) to build the decision matrix for multi-criteria evaluation [17].

Table 1: A detailed description of properties related to DEM data

	Satellite/Sensor Path/Row Date Acquired	Spatial Resolution (m)	Description
1	Shuttle Radar Topographic Mission 23 -9- 2014	30	Digital Elevation Model Generated from SRTM, UTM -WGS 1984, Zone 38 N

2.2.2 Selection of Evaluation Criteria

The selection of evaluation criteria was guided by three primary considerations: hydrological relevance to runoff generation and storage, data availability and reliability, and applicability to regional-scale centralized rainwater harvesting planning. Accordingly, six DEM-derived criteria were selected to represent the key topographic and hydrological controls influencing surface runoff convergence and retention.

In the initial planning phase, other criteria were taken into consideration, like intensity of rainfall, soil type, land use/land cover and socio-economic limitations[18]. Nevertheless, these variables did not go through to the final evaluation because there was a limitation of spatial resolution, high time variance or absence of consistent and reliable datasets throughout the study area. The last 6 criteria, including mean slope, mean elevation, mean curvature, mean log-transformed flow accumulation, mean distance to streams and site area then were chosen to provide balanced and physically significant portrayals of the terrain controlled hydrological processes involved in governing centralized RWH suitability with transparency and reproducibility in the methods.

Table 2: Evaluation criteria for RWH site ranking (DEM-derived)

Code	Criterion	Preference	Notes
C1	Mean slope (°)	Cost	Lower slope favors ponding + reduces excavation risk
C2	Mean log (flow accumulation)	Benefit	Larger contributing flow → higher runoff supply
C3	Mean elevation (m)	Cost	Lower elevation supports gravity-driven convergence
C4	Mean absolute curvature	Cost	Near-zero curvature is preferred (stable terrain)
C5	Mean distance to streams (m)	Cost	Smaller distance improves capture feasibility
C6	Area (km^2)	Benefit	Larger footprint increases storage potential

Candidate RWH sites were delineated as discrete polygons based on hydrological accumulation thresholds and terrain constraints.

2.3 Methodology

2.3.1 Entropy Weight Method (EWM)

Entropy Weight Method (EWM) is an objective weighting method that is based on information theory whereby the weights of the criterion are derived from the extent of variation in the decision matrix and not on subjective assessment [19,20]. This method has a theoretical basis that was first proposed by Shannon, and later by Zaleny, which allows quantifying information represented in every criterion depending on the variability of the data [21,22]. With its capacity of minimizing subjectivity and enhancing reproducibility, entropy weighting has been extensively used in environmental and water-resources decision-making problems. In this research, the EWM was used to objectively estimate the relative value of the chosen evaluation criteria using their statistical properties only. A decision matrix $X = [x_{ij}]$was constructed from the mean criterion values extracted for the $m$candidate sites and n criteria. The matrix was normalized using entropy normalization as expressed in Equation 1.

$$r_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \tag{1}$$

where r_{ij} represents the normalized value of criterion j for alternative i.
Subsequently, the entropy value for each criterion was calculated using Equation 2.

$$e_j = -k \sum_{i=1}^{m} r_{ij} \ln r_{ij}\,, \;\; k = \frac{1}{\ln(m)} \tag{2}$$

where e_j denotes the entropy of criterion j, and k is a normalization constant ensuring that $0 \leq e_j \leq 1$.
The degree of diversification (or information utility) for each criterion was then computed using Equation 3:

$$d_j = 1 - e_j \tag{3}$$

Finally, the normalized entropy weight W_j for each criterion was obtained according to Equation 4:

$$W_j = \frac{d_j}{\sum_{j=1}^{n} d_j} \tag{4}$$

The criteria with a greater variability across sites attained greater weight, indicating that they have greater discriminatory capacity to rank sites. The weights derived out of entropy were in turn employed as inputs to the TOPSIS model so that prioritization of final sites could be achieved.

The candidates centralized rainwater harvesting sites were identified as 23 sites on the basis of hydrological and geomorphological screening of the datasets based on DEM. Candidate site number was not pre-determined but was obtained by the use of objective spatial thresholds based on flow accumulation, slope and terrain continuity which maintained only hydrologically significant and spatially independent sites. Flow accumulation thresholds were applied to define contributing catchments that could produce enough runoff and slope and curvature restrictions were used to exclude the areas that had an adverse terrain which would support water storage and stability of infrastructures. Neighbouring polygons of similar hydrological nature were also consolidated and isolated or marginal features were eliminated to prevent redundancy and excessive fragmentation. This systematic filtering process left 23 candidate polygons which were then assessed in terms of the entropy weighted TOPSIS framework. Table 3 gives the mean values of the selected DEM-derived criteria of these 23 potential sites to create the decision matrix of multi-criteria ranking.

Table 3: Decision Matrix of DEM-Derived Criteria of the 23 Candidate Rainwater Harvesting Sites (Mean Values and Polygon Area)

Site ID	Slope_ mean	Curvature_ mean	LogFA_ mean	DistStr_ mean	Elev_ mean	Area_ Km^2
S1	3.206	0.007	0.536	346.265	39.536	1.134
S2	3.487	0.006	0.556	1329.692	41.742	2.370
S3	3.223	0.013	0.596	1788.489	43.708	1.312
S4	3.512	0.005	0.582	2082.995	42.353	1.132
S5	3.591	-0.001	0.639	948.564	41.638	3.625
S6	3.716	0.011	0.488	1598.241	35.378	7.006
S7	3.819	0.009	0.521	2443.549	41.212	5.592
S8	3.739	0.005	0.502	2434.070	39.904	1.156
S9	3.565	0.003	0.605	2736.829	40.532	6.271
S10	3.705	0.005	0.512	2388.278	41.008	5.627
S11	3.437	-0.003	0.563	1704.394	44.230	1.085
S12	3.849	-0.002	0.560	1605.932	47.060	1.453
S13	2.703	0.000	0.569	2501.101	33.544	1.225
S14	2.473	-0.002	0.691	2371.399	33.668	1.509
S15	2.909	-0.001	0.693	740.147	34.088	4.315
S16	2.846	0.005	0.722	1546.624	33.066	1.521
S17	3.742	0.005	0.513	837.156	52.391	1.384
S18	2.619	-0.009	0.978	96.153	29.531	1.869

S19	4.066	0.001	0.598	1769.672	60.677	27.921
S20	3.737	0.003	0.560	1759.823	81.713	3.683
S21	4.457	0.002	0.599	2814.896	95.207	1.706
S22	4.129	0.002	0.580	2593.234	103.350	3.834
S23	3.533	-0.001	0.586	2624.928	113.762	2.836

2.3.2 TOPSIS Ranking

The Technique for Order of Preference by Similarity to an Ideal Solution (TOPSIS) is a widely used multi-criteria decision-making method that ranks alternatives based on their relative distances from a positive ideal solution and a negative ideal solution [23,24]. Owing to its conceptual simplicity and its ability to simultaneously handle both benefit and cost criteria, TOPSIS has been extensively applied in hydrological planning and site-selection problems. In the present study, TOPSIS was employed to rank the candidate centralized rainwater harvesting sites using the entropy-derived criterion weights obtained in the previous step. The normalized decision matrix was first multiplied by the entropy weights to generate the weighted normalized matrix. Subsequently, the positive ideal solution A^+ and the negative ideal solution A^- were defined by selecting the maximum values for benefit criteria and the minimum values for cost criteria, respectively. The Euclidean distance of each alternative from the positive ideal solution D_i^+ and the negative ideal solution D_i^- was then computed. Based on these distances, the closeness coefficient C_i, which represents the relative suitability of each candidate site, was calculated using Equation 5:

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-} \quad (5)$$

A higher value of C_i indicates greater similarity to the ideal solution and, consequently, higher suitability for centralized rainwater harvesting implementation. The resulting TOPSIS distances, closeness coefficients, and final rankings for the 23 candidate sites are presented in Table 4.

Table 4: TOPSIS Results of Candidate Rainwater Harvesting Sites with Distances to Ideal Solutions and Coefficient of Closeness

Site ID	S_plus	S_minus	Closeness_C	TOPSIS_Rank
S19	0.008	0.555	0.986	1
S9	0.441	0.135	0.235	2
S6	0.434	0.123	0.221	3
S10	0.455	0.115	0.201	4
S15	0.481	0.118	0.197	5
S5	0.495	0.111	0.184	6

S7	0.460	0.098	0.176	7
S22	0.491	0.100	0.170	8
S20	0.494	0.097	0.165	9
S23	0.511	0.100	0.163	10
S13	0.543	0.101	0.156	11
S21	0.534	0.088	0.142	12
S14	0.538	0.088	0.140	13
S12	0.539	0.086	0.138	14
S11	0.547	0.080	0.128	15
S8	0.546	0.067	0.110	16
S2	0.522	0.063	0.107	17
S16	0.539	0.063	0.105	18
S17	0.542	0.063	0.104	19
S4	0.547	0.062	0.102	20
S1	0.548	0.049	0.082	21
S18	0.535	0.039	0.068	22
S3	0.551	0.0170	0.030	23

2.3.3 Sensitivity Analysis

In order to test the strength of the results of the TOPSIS-based ranking, a sensitivity analysis was performed by changing the weights of each individual criteria and ensuring that the other weights are changed accordingly[25,26]. The analysis sought to test a hypothesis of the ability of moderate variations in criterion importance to substantially alter the overall ranking structure. The findings suggest that a structure of ranking is not significantly changed when there are moderate weight perturbations. Specifically, the top-ranked sites (e.g., S19, S9, and S6) were the ones that remained at the top positions regardless of the weights of the dominant criteria, reduced or increased within the limits of practicality (i.e., site area and flow accumulation). Such a pattern indicates that the superiority of such sites cannot be motivated by one factor, but it is based on a positive mixture of multiple hydrological and terrain factors. There was minimal fluctuation in the ranks of the mid-ranked alternatives and these were mostly similar in the value of the closeness coefficient. Yet, these modifications had no influence on the decision of highly suitable and less suitable sites, which is the main aim of the decision support process. Notably, none of the lowest suitability group of sites shifted into the highest weighting scenario category.

In general, the sensitivity analysis demonstrates the fact that the offered entropy-TOPSIS model yields consistent and credible ranking results, which further supports its applicability to real-world implementation in centralized rainwater harvesting planning.

3. Results and Discussion

The outcomes of the entropy weighting show that the most discriminatory criteria between the considered criteria are the site area (C6) and the log-transform flow accumulation (C2). This result emphasizes the prevailing role of runoff supply capacity and possible storage footprint in establishing the appropriateness of centralized locations of rainwater harvesting. Conversely, the mean elevation (C3) and the absolute curvature (C4) have relatively lower impact, mainly because they have a small range of variability in the defined candidate polygons. According to the weights of the entropy analysis, the TOPSIS analysis resulted in a clear and consistent division of highly fitting and less preferable alternatives.

As shown in Table 4, site S19 had the highest closeness coefficient (C i=0.9859), which means that it is very similar to an ideal solution. S9, S6, S10, and S15 follow S1, and they all reveal relatively high scores of suitability. The overall results of the DEM-derived criteria of the top-ranked sites are represented in Table 5.

Table 5: Mean Values of DEM-Derived Criterion of the Top-Ranked Rainwater Harvesting Sites Selected by TOPSIS

Site ID	Slope_ mean	Curvature_ mean	LogFA_ mean	DistStr_ mean	Elev_ mean	Area_ Km^2
S6	3.716	0.011	0.488	1598.241	35.378	7.006
S9	3.565	0.002	0.605	2736.829	40.532	6.271
S10	3.706	0.005	0.512	2388.278	41.008	5.627
S15	2.909	-0.001	0.693	740.147	34.088	4.315
S19	4.066	0.001	0.598	1769.672	60.677	27.921

The characteristics that define these locations are typically larger areas of polygons, greater contributing flow accumulation and favorable geography including low slopes and decent access to the stream network. As an example, S19 has a significantly greater area than other candidates, whereas S9 and S6 have moderate slope with large flow accumulation values, which increases their prospects of effective runoff capture and storage.

Spatial distribution of the suitability results can be demonstrated by Figure 4 ,where yellow polygons denote higher ranking of the sites. It is evident in the map that the locations, whose characteristics involve large contributing catchments and good geomorphology to hydrology, will be assigned higher scores in the preference. On the other hand, candidate sites that have low contributing area or are far away in terms of distance to the derived drainage network would have low suitability rankings.

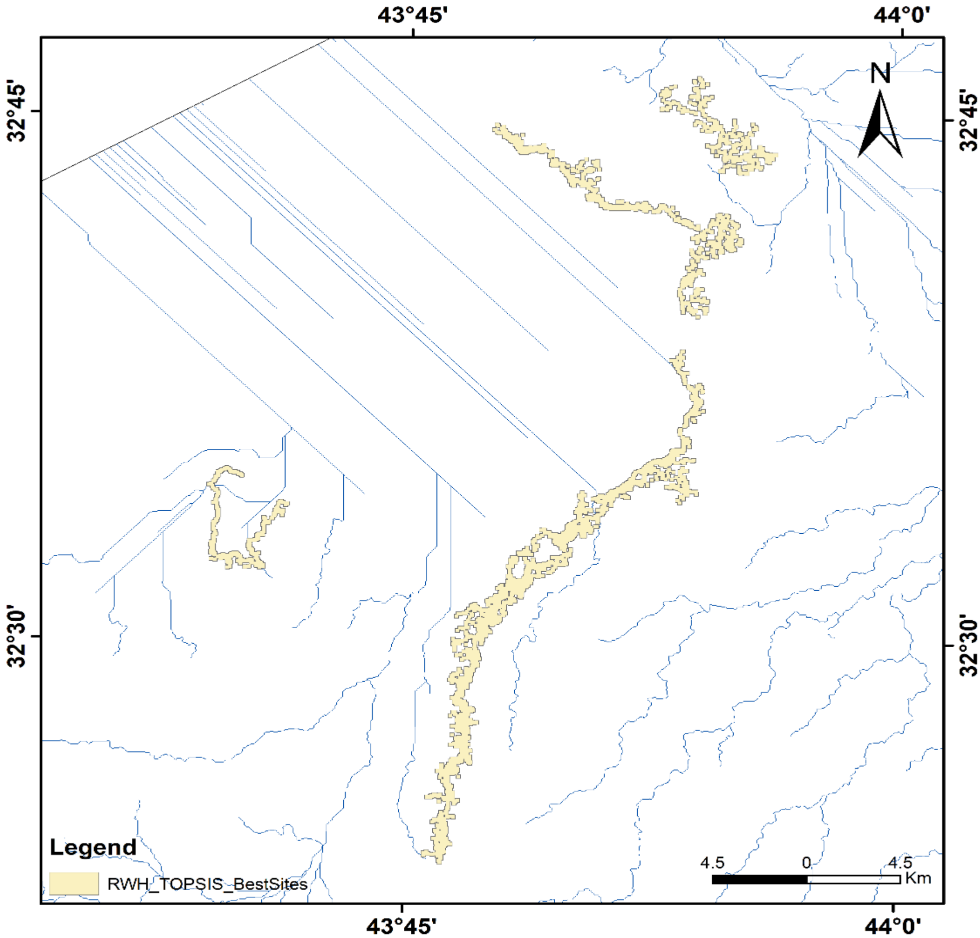

Figure 4: TOPSIS-based suitability ranking of potential centralized rainwater harvesting sites in Karbala Province, Iraq

Sensitivity analysis also indicates that the results of TOPSIS ranking are sound. Even though slight rank changes were noted in the mid-ranking alternatives with moderate weight perturbations, the first- and last-ranked sites did not change substantially. It shows that the identified priority sites do not change significantly with minor changes in the criterion weights, which strengthens the validity of the proposed entropy-TOPSIS framework in practice-oriented rainwater harvesting planning.

Overall, the findings indicate that the suitability of centralized rainwater harvesting in Karbala Province is mainly dictated by the catchment-scale hydrological features as opposed to some topographic peculiarities. The agreement of entropy weighting, TOPSIS ranking and spatial mapping helps to verify the internal consistency of methodology and its potential to apply to similar arid and semi-arid environments.

4. Conclusion

This paper constructed an objective GIS-based decision-support model of determining the appropriate location of centralized rainwater harvesting by entropy-weighted TOPSIS and DEM-generated hydrological indices. The proposed methodology reduces subjective judgment and promotes transparency and reproducibility since it relies on the terrain-controlled variables and weighs objectives. The findings show site area and flow accumulation have the highest impact on site suitability as the entropy weighting and TOPSIS ranking results indicate. Sites with greater contributing catchments and greater runoff convergence had always scored highest on suitability, with elevation and terrain curvature having a secondary influence on suitability since they varied the least across the study area. The framework applied to Karbala Province showed that there was a definite spatial distinction between the highly suitable and less favorable areas with the highest rank sites featuring hydrologically favorable terrain conditions to capture and store runoffs. Sensitivity analysis also supported the fact that the ranking outcome does not change drastically with moderate differences between criterion weights, which indicates the strength of the suggested method. In general, the results indicate that the applicability of centralized rainwater harvesting to arid and semi-arid settings is mostly dictated by the hydrology at the catchment scale as opposed to individual topographical variables. The suggested GIS-entropy-TOPSIS framework will be an effective and transferable unit to assist the long-term water resources planning and sustainable development of infrastructure in regions with scarce data.

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ترتيب مواقع حصاد مياه الأمطار المركزية باستخدام نموذج Entropy–TOPSIS القائم على نظم المعلومات الجغرافية والمؤشرات الهيدرولوجية المستخرجة من نموذج الارتفاعات الرقمية: محافظة كربلاء، العراق

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المستخلص: تُعد ندرة المياه من أبرز المشكلات البيئية في المناطق الجافة وشبه الجافة، نتيجة التوزيع غير المنتظم للأمطار، والنمو السكاني المتسارع، وتزايد الضغوط على مصادر المياه التقليدية. وتمثل أنظمة حصاد مياه الأمطار المركزية خيارًا تقنيًا مستدامًا لتعزيز الموارد المائية؛ إلا أن كفاءتها تعتمد بدرجة كبيرة على حسن اختيار المواقع المناسبة لتنفيذها. وبناءً على ذلك، تقترح هذه الدراسة نموذجًا داعمًا للقرار قائمًا على نظم المعلومات الجغرافية، يدمج بين المؤشرات الهيدرولوجية المستخرجة من نموذج الارتفاعات الرقمية (DEM) وإطار موضوعي لاتخاذ القرار متعدد المعايير، بهدف تحديد المواقع الأنسب لتطبيق أنظمة حصاد مياه الأمطار المركزية في محافظة كربلاء، العراق. اعتمادًا على بيانات مهمة المكوك الراداري الطبوغرافي (SRTM) والتحليل المكاني، تم اشتقاق ستة معايير فيزيائية ذات دلالة هيدرولوجية، تشمل: متوسط الانحدار، ومتوسط الارتفاع، ومتوسط الانحناء، ومتوسط اللوغاريتم المحول لتراكم الجريان، ومتوسط المسافة إلى المجاري المائية، ومساحة الموقع. ولتقليل التحيز الذاتي في تحديد أوزان المعايير، تم استخدام طريقة الوزن بالإنتروبيا لتقدير الأهمية النسبية لكل معيار بصورة موضوعية. بعد ذلك، استُخدمت تقنية تفضيل البدائل حسب قربها من الحل المثالي (TOPSIS) لترتيب 23 موقعًا مرشحًا وفق درجة قربها من الحل المثالي. وأظهرت النتائج أن مساحة الموقع وتراكم الجريان يمثلان العاملين الأكثر تأثيرًا في ملاءمة المواقع، في حين أن الارتفاع والانحناء يسهمان بنسبة أقل نسبيًا في التقييم العام للملاءمة.

الكلمات المفتاحية: حصـــــاد مياه الأمطار؛ نظم المعلومات الجغرافية؛ طريقة الوزن بالإنتروبيا؛ TOPSIS؛ هيدرولوجية نموذج الارتفاعات الرقمية؛ محافظة كربلاء؛ العراق

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