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Using multi-criteria spatial analysis to identify potential water harvesting locations

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Abstract

Water resources are one of the most important requirements for building societies and one of the basic components of development, especially in arid and semi-arid regions due to the limited rainfall and its distribution and the lack of water availability in light of the increasing population growth and the declining quality of water resources due to various pollution factors. Therefore, the integrated management of these resources has become extremely important to maintain water security in order to avoid future crises resulting from water shortages in quantity and quality. From this standpoint, this research aims to find sources of water by exploiting the available surface runoff using water harvesting technology, by introducing a number of factors affecting water harvesting in the study area, which are: slope, rainfall, geological structures, soil, and drainages. Depending on the opinions of local experts, the importance (weight) of each influential factor was obtained through the hierarchical analysis method, and using geographic information system techniques, processing, analysis, and weighted linear combination of the maps representing these factors were carried out. As a result, a suitability map of water harvesting sites in the studied area was obtained, which was divided into three sectors (high, medium, low) after excluding inappropriate sites from the map such as wells, faults, and cities. The results reached through this research contribute to reduce the gap between available resources and the demand for them in order to achieve sustainable development of these resources

Keywords: Water Harvesting, Sustainable Development, Geographic Information System, Water Security.

استخدام التحليل المكاني متعدد المعايير لتحديد المواقع المحتملة لحصاد المياه

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الملخص

تعدُ الموارد المائية واحدة من أهم متطلبات بناء المجتمعات وإحدى المقومات الأساسية للتنمية خاصة في المناطق الجافة وشبه الجافة بسبب محدودية الأمطار وتوزعها وقلة توفر المياه في ظل النمو السكاني المتزايد وتدني جودة الموارد المائية من جراء عوامل التلوث المختلفة، وبالتالي فإنَ الإدارة المتكاملة لهذه الموارد أصبح من الأمور البالغة الأهمية للحفاظ على الأمن المائي وذلك لتجنب أزمات مستقبلية تنجم عن نقص المياه كماً ونوعاً. ومن هذا المنطلق يهدف هذا البحث إلى إيجاد مصادر للمياه من خلال استغلال الجريان السطحي المتوفر باستخدام تقنية حصاد المياه وذلك من خلال إدخال عدد من العوامل المؤثرة على حصاد المياه في منطقة الدراسة وهي: الميل، الهطول المطري، التراكيب الجيولوجية، التربة، المسيلات. وبالاعتماد على آراء الخبراء المحليين تم الحصول على أهمية (وزن) كل عامل مؤثر من خلال طريقة التحليل الهرمي، وباستخدام تقنيات نظام المعلومات الجغرافي تم إجراء عمليات المعالجة والتحليل والدمج الخطي الموزون للخرائط الممثلة لهذه العوامل وبالنتيجة تم الحصول على خريطة الملاءمة لمواقع حصاد المياه في المنطقة المدروسة والتي قسمت إلى ثلاثة قطاعات (عالية، متوسطة، منخفضة) وذلك بعد استبعاد المواقع غير الملائمة من الخريطة مثل الآبار، الفوالق، المدن. والنتائج التي تم التوصل إليها من خلال هذا البحث تساهم في تقليل الفجوة بين الموارد المتاحة والطلب عليها بما يحقق التنمية المستدامة لهذه الموارد.

الكلمات المفتاحية – حصاد المياه، التنمية المستدامة، نظام المعلومات الجغرافية، الأمن المائي.

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Introduction

Proper investment of water resources for drinking, agriculture, industry and other uses requires evaluating these resources in terms of quantity and quality, especially in light of increasing climate change, scarcity of fresh water sources and declining groundwater levels. Therefore, it is necessary to choose the appropriate method for optimal investment of available water, as rainwater harvesting is considered one of the most important techniques that humans have used since ancient times in areas with dry climates and little rain, to benefit from it for economic purposes [Abeer Manla Hassan, Iskandar Ismail and Kamel Shadid 2009]. and these techniques include building small earthen barriers (dams) in flood areas, as well as building basins and pits, which contribute effectively to various agricultural and population activities, according to specific conditions and standards that achieve the purpose of the required study[Al- Amoush ,et al, 2012] [Kadam,et al,2012]. It must be known that the success of water harvesting operations varies from one geographical location to another according to a set of environmental factors affecting the nature of the region, due to the difference in rainfall rates, the main determinant of water harvesting operations. In addition to the differences in land uses, soil characteristics, surface slopes and other factors that determine the feasibility of water harvesting projects [Girish, 2008].

Reference studies

There are many studies that have been applied in arid and semi-arid regions to determine the optimal locations for harvesting rainwater based on a number of influential factors and using multi-criteria decision-making tools. The great development that has occurred, whether in work methods or in possessing technologies and software or in the field of acquiring skills and experiences, has led to saving a lot of effort and time and giving more accuracy in the applied results of these studies [DUC,2006] [SAATY,2008]. Hence, the use of Geographic Information System (GIS) techniques was used to optimally select sites for the construction of dams and barrages (small dams) to make the most of rainwater in the desert region. The geographic information system enables the necessary analyses to be carried out on data in its spatial and descriptive form, linking them together, and carrying out the required quantitative and descriptive assessments. Thus, a new map, derived data, or both can be easily obtained, and this map carries predictions or conclusions according to a systematic plan that is developed in advance [Reem Ammar, Rafiq Jabr and Abdelmajid Al-Kafri, 2015.Which helps in reducing expenses, saving effort, increasing production, and achieving high accuracy in implementing the task if we compare implementing a task with traditional methods, given the advanced processing methods of this system [Mohamed, et al, 2008]. The hierarchical analysis process also represents the most important tools used for this purpose, through knowing the problem and the criteria affecting it and the binary comparison between the main and secondary criteria with each other. The comparison is made using the opinions of a group of local experts, and thus the weight of the influential factors is estimated for the goal [Saaty et al, 2006].In a study conducted to estimate the potential of water harvesting in the Mujib Basin in Jordan, based on descriptive and spatial cartographic data on natural and human resources in the water basin, to produce the digital maps necessary for spatial analysis, the maps required to build a spatial model to determine the optimal locations for establishing water harvesting projects were presented. The most important practical solutions proposed to determine the best water harvesting locations that can be established in the basin were presented. In addition to the proposals that are suitable for secondary water basins, based on a set of criteria that were used and that are compatible with the nature of the region [Alzghoul,et al,2020] . A set of criteria was reached through which the foundations were laid for selecting the sites for earthwork excavations, which were represented by the rainfall criteria, soil texture, slope, distance from faults, and distance from valleys. Distance from roads, distance from international borders, and thematic maps related to these criteria were prepared using the GIS program, then the appropriate weighting process was carried out for each influential criterion using the hierarchical analysis method. Thus, making the appropriate decision to identify potential sites for rainwater harvesting in the southern basin lands that are close to the main tributaries of the valley [AL-Adamat,et al, 2010].

Research Materials and Methods:

Objective of the research:

The research aims to identify potential sites for water harvesting using a hierarchical analysis method that uses references and opinions of local experts in determining the weight of influencing factors, and then conducting a weighted linear integration process of the used maps classified and representative of the mentioned factors using GIS software.

Data used:

To obtain the desired objective of the study using the Geographic Information System (GIS) and the Analytic Hierarchy Process (AHP), the following data was used [General Organization for Remote Sensing (GORS), 2016]:

- Geological map at a scale of 200000/1, where geological formations and faults are mapped.
- Topographic map at a scale of 1:50,000, where waterways, elevations, Digital Elevation Model (DEM) and slopes were extracted.
- Rainfall distribution map, from which the distribution of annual rainfall rates in the studied area was obtained.
- Soil distribution slide in the study area.
- Slides of wells and cities in the study area.

Study area:

The study area is located about 45 km northeast of Homs Governorate and Figure (1) defines the geographical extension of the study area between:

Latitudes 34°30'N and 34°45'N. Longitude 37°15' and 37°45' East.

Topographically, the area is characterized by the fact that it extends within the foothills of the foothills of the medium to low-altitude Palmyrene Mountains, and the topographic surface is slightly undulating with low to moderate slopes.) The topographic elevation ranges from (1235) meters in the northeast, and the lowest point is located in the extreme southeast with a height of (675) meters above sea level as shown in the Digital Elevation Model (DEM) of the study area in Figure (2). The studied area is dominated by the influence of the dry climate and extends in several stability zones (third, fourth and fifth) where the value of rainfall ranges from 150 mm/year to 300 mm/year as shown in Figure (3) [General Organization for Remote Sensing (GORS), 2016]:

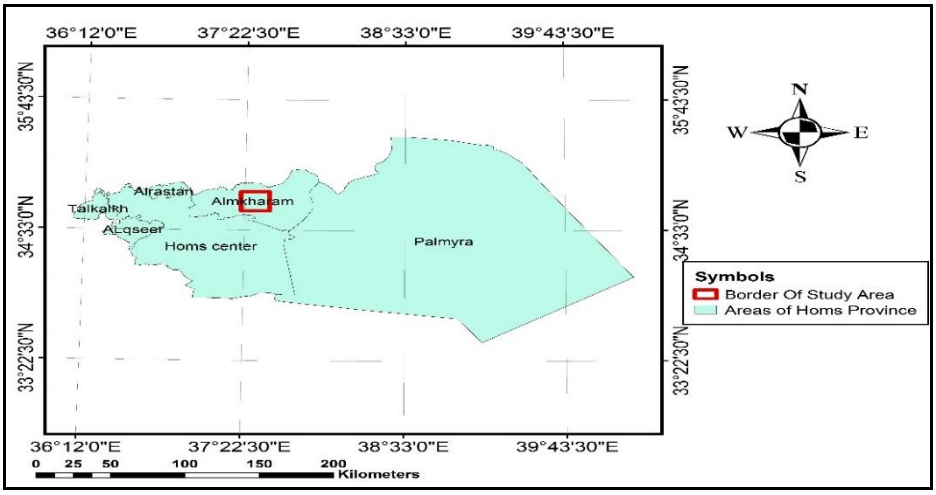

Figure (1): Geographical extension of the study area

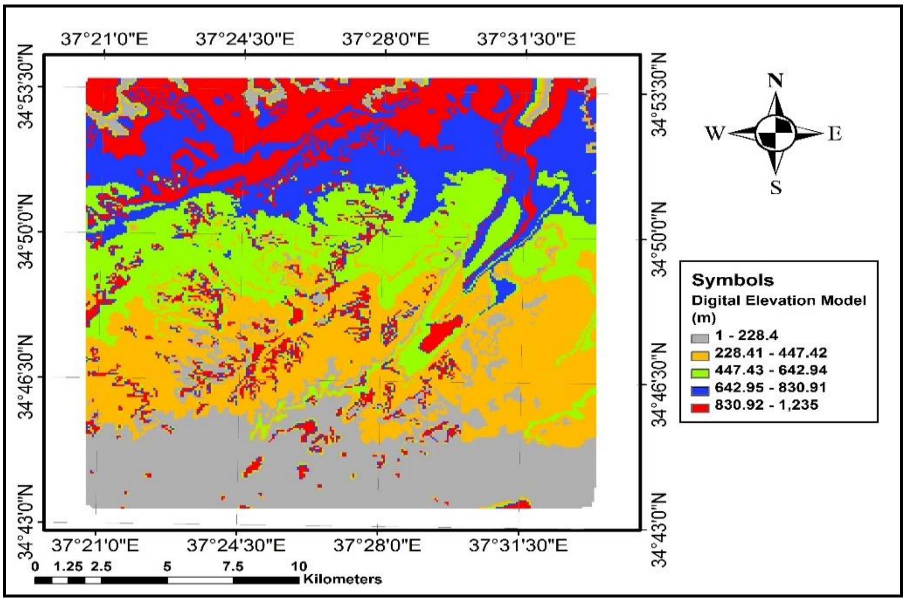

Figure (2): Digital Elevation Model Dem for the study area

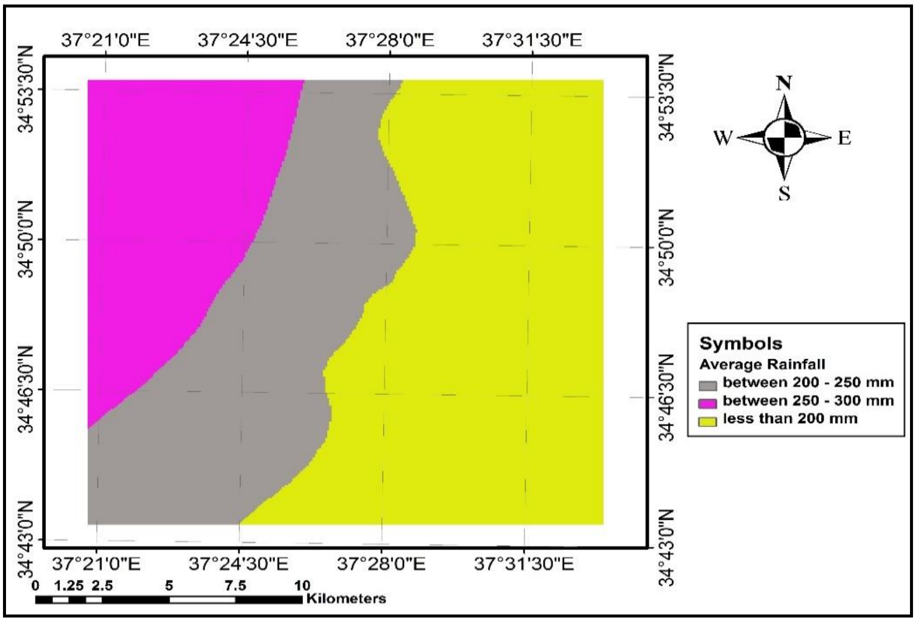

Figure (3): Rainfall distribution in the study area

Hierarchical analysis method:

The AHP method is one of the multi-criteria decision analysis (MCDA) tools developed by Satty. It is used to calculate weights for a criterion (scale) based on conflicting expert opinions, it is an uncommon method that alleviates the need to gather experts in one place, in addition to being an important method in determining weights when data is limited. This method has been applied by many researchers in many parts of the world such as Tunisia, Spain, Vietnam, and Middle Eastern countries in the field of identifying potential sites for water harvesting**.** [ANANE, et al,2008];] [AZNAR, et al, 2005]; [GHAMGOSAR, et al ,2008]; [DUC, 2006]. AHP is based on creating a series of paired comparison matrices (PCMS), which involves comparing all possible pairs of criteria to determine which criteria have a higher priority [SAATY, 1990]. Satty proposed a scale (1-9) for PCMS items as shown in Table 1, where the value (1) indicates the scale of equal importance, while the value (9) indicates that the scale considered is very important compared to the other scale.

Table (1): Measures of the paired comparison method [SAATY, 1980]

Importance severity	Definition	Explanation
1	Important Pair	Two contributing criteria of equal importance to the goal
3	Moderately important	Opinion or experience that slightly favors one criterion over the other
5	Strongly important	Opinion or experience strongly favors one criterion over the other
7	Very Strongly Important	Opinion or experience very strongly favors one criterion over the other
9	Excellent importance	Evidence favoring one criterion with the highest possible credibility
2,4,6,8	Medium values	When compromise is required

PCMS includes a consistency test where the errors of judgment are determined and the consistency ratio is calculated by following the following steps [SAATY, 2008]:

- Identify the important metric in the issue Evaluating the importance of each criterion relative to the other is usually done by experts using a scale (1-9) and this step involves three main procedures:
- Calculating the priority vector of the scale or calculating the paired comparison matrix of the criteria.
- Calculate the linear transformation coefficient (Principal Eigen Value) from the equation (1):

$$(1) \quad \lambda_{max} = \frac{\sum sum}{n}$$

- The linear transformation coefficient λ_{max} ; ∑Sum: The sum of the columns or lines in the matrix; n: Number of criteria
- Calculate the CI (The index of congruence), which gives information about the logical match between two opinions for a complete comparison. If CI=0, there is no logical match between paired comparisons or the percentage of mismatch is 100%, and the CI is calculated from the equation (2):

$$CI = \frac{\lambda_{max} - n}{n - 1} \qquad (2)$$

- Determine the estimated value of the random match ratio and its symbol RI as shown in Table 2.
-

Table(2): Mean values of the randomized average match index for different number of criteria [SAATY, et al, 2006]

Number of standards	1	2	3	4	5	6	7	8
Random Identity Index (RI)	0	0	0.58	0.90	1.12	1.24	1.32	1.41
Number of standards	9	10	11	12	13	14	15	-
Random Identity Index (RI)	1.45	1.49	1.51	1.54	1.56	1.57	1.59	-

- Calculate Match ratio CR, which is a comparison between the match index and the random match index and it is calculated from the equation (3). If the value of the match ratio is less than or equal to 10%, the mismatch is acceptable, and conversely, if the match ratio is greater than 10%, the expert's opinion should be rejected.

$$CR = \frac{CI}{RI} \leq 0.1 \qquad (3)$$

To identify potential water harvesting sites, weights and rankings for each influencing factor were determined, and expert opinions and references were used to select five physical criteria: Rainfall, Slope, Linearity, Flooding, and Geology. On the other hand, the Analytic Hierarchy Process (AHP) viewpoint was used to evaluate the agreement between experts' opinions by using the congruence ratio (CR), which should be less than or equal to 10%, and thus weights were determined for these criteria. The rating for each criterion was assessed with a scale (5-1), which was adopted by most of the relevant references. [Youssef, et al, 2010].

Table (3) shows the values of the paired comparison matrix scales according to five local experts specialized in water harvesting issues in the field of geology, hydrogeology, civil engineering (water resources), groundwater, geographic information system (GIS). Face-to-face interviews were conducted to determine the importance of each criterion influencing the water harvesting issue using the scale (9-1). Tables (4,5,6,7,8) show the paired comparison matrix according to each expert for the selected criterion. Table (9) shows the paired comparison matrix according to the average.

Table(3): Scale values for the paired comparison matrix according to the five experts

	Expert1	2 Expert	3 Expert	4 Expert	5 Expert
Slope	7	8	7	6	8
Rainfall	6	6	5	5	5
Geology	8	7	8	7	8
Drainages	6	4	5	5	6
Soil	5	5	4	4	4

Table (4): Pairwise comparison matrix according to the first expert

Factor	Slope	Rainfall	Geology	Drainages	Soil
Slope	1	1.166	0.875	1.166	1.4
Rainfall	0.857	1	0.75	1	1.2
Geology	1.142	1.333	1	1.333	1.6
Drainages	0.857	1	0.75	1	1.2
Soil	0.714	0.833	0.625	0.833	1
Sum	4.571	5.332	4	5.332	6.4
Weight	22.58	19.35	22.58	19.35	16.12
λmax = 5.126 ≥ 5 ok CI=0.0317, RI=1.12, CR=0.028 ≤ 0.1→ok					

$$\lambda max = \frac{\sum sum}{n} \geq n \qquad \ldots\ldots \quad (1)$$

$$CR = \frac{CI}{RI} \leq 0.1 \qquad \ldots\ldots \quad (2)$$

$$CI = \frac{\lambda\, max - n}{n-1} \qquad \ldots\ldots \quad (3)$$

λ_{max}: Linear transformation coefficient, CI: index of congruence

RI: Randomized Index of Congruence (obtained from Table 2 by number of criteria)

CR: Congruence ratio, n: Number of criteria (five in the research), Sum :∑The sum of the columns or lines in the matrix

Table(5): Pairwise comparison matrix according to the second expert

Factor	Slope	Rainfall	Geology	Drainages	Soil
Slope	1	1.333	1.142	2	1.6
Rainfall	0.75	1	0.857	1.5	1.2
Geology	0.875	1.166	1	1.75	1.4
Drainages	0.5	0.667	0.571	1	0.8
Soil	0.625	0.833	0.714	1.25	1
Sum	3.75	4.999	4.284	7.5	6
Weight	24.24	18.18	21.21	21.21	15.16
$\lambda max = 5.3066 \geq 5$ ok CI=0.07665, RI=1.12, CR=0.068 $\leq 0.1 \rightarrow$ ok					

Table (6): Pairwise comparison matrix according to the third expert

Factor	Slope	Rainfall	Geology	Drainages	Soil
Slope	1	1.4	0.875	1.4	1.75
Rainfall	0.714	1	0.625	1	1.25
Geology	1.142	1.6	1	1.6	2
Drainages	0.714	1	0.625	1	1.25
Soil	0.571	0.8	0.5	1	1
Sum	4.141	5.8	3.625	0.8	7.25
Weight	24.14	17.24	27.57	17.25	13.80
$\lambda max = 5.323 \geq 5$ ok CI=0.0808, RI=1.12, CR=0.072 $\leq 0.1 \rightarrow$ ok					

Table (7): Pairwise comparison matrix according to the fourth expert

Factor	Slope	Rainfall	Geology	Drainages	Soil
Slope	1	1.2	0.857	1.2	1.5
Rainfall	0.833	1	0.714	1	1.25
Geology	1.166	1.4	1	1.4	1.75
Drainages	0.833	1	0.714	1	1.25
Soil	0.666	0.8	0.571	0.8	1
Sum	4.498	5.4	3.856	5.4	6.75
Weight	22.23	18.52	25.92	18.52	14.81
$\lambda max = 5.1808 \geq 5$ ok CI=0.0452, RI=1.12, CR=0.040 $\leq 0.1 \rightarrow$ ok					

Table (8): Pairwise comparison matrix according to the fifth expert

Factor	Slope	Rainfall	Geology	Drainages	Soil
Slope	1	1.6	1	1.333	2
Rainfall	0.625	1	0.625	0.833	1.25
Geology	1	1.6	1	1.333	2
Drainages	0.75	1.2	0.75	1	1.5
Soil	0.5	0.8	0.5	0.667	1
Sum	3.875	6.2	3.875	5.166	7.75
Weight	25.81	16.13	25.81	19.35	12.90
λmax = 5.3732 ≥ 5 ok CI=0.0933, RI=1.12, CR=0.083 ≤ 0.1→ok					

Table (9): Pairwise Comparison Matrix by Mean

Factor	Slope	Rainfall	Geology	Drainages	Soil
Slope	1	1.4	0.875	1.4	1.75
Rainfall	0.714	1	0.625	1	1.25
Geology	1.143	1.6	1	1.6	2
Drainages	0.714	1	0.625	1	1.25
Soil	0.571	0.8	0.5	0.8	1
Sum	4.142	5.8	3.625	5.8	7.25
Weight	24.14	17.24	27.60	17.24	13.78
λmax = 5.323 ≥ 5 ok CI=0.08085, RI=1.12, CR=0.072 ≤ 0.1→ok					

Geographic Information System (GIS):

From the application of the Geographic Information System (GIS), representative diagrams were obtained for the factors that were included in the identification of potential groundwater locations (geology, waterways, slope, rainfall, and soil)**.**

3.5.1 Geology: From the geological map with a scale of 200000/1, it is clear that the rocks exposed in the study area are of Cretaceous, Paleogene, Neogene and Quaternary ages (Figure: 4), where the Cretaceous (Cr) period is characterized by the following deposits:

- Middle Cretaceous composed of dolomitic limestone and sandstone with flint intrusions.
- Upper Cretaceous is composed of dolomitic limestone, marl, and chert.
- The rocks of the Quaternary-Q period belong to the Middle, Upper, and Recent periods, and consist of fossil terraces, pebbles, sandstone, silt, and sand.
- Neogene epoch: N is of Pliocene and Middle Miocene ages and the lithology consists of limestone, sandstone, conglomerate, conglomerate, and marl. - Paleogene epoch: Pg and belongs to the Paleocene, Middle and Upper Eocene ages and the rocky medium consists of limestone, limestone, gabbro, gabbro and marl.

3.5.2 Slope: Through the use of topographic maps in the study area, a slide of the distribution of Slope in the study area was created as shown in Figure (5), where most of the study area is plain and interspersed with some depressions.

3.5.3 Drainages: From the topographic map (1/50000 scale) and the satellite image, the distribution of the drainages network in the study area was established as shown in Figure (6). These drainages are characterized by regular distribution in the study area. From the distribution of the drainage network, the density of drains in the study area was established, which is the unit of measurement per square kilometer, as shown in Figure (7), where the highest density is concentrated in the southeast.

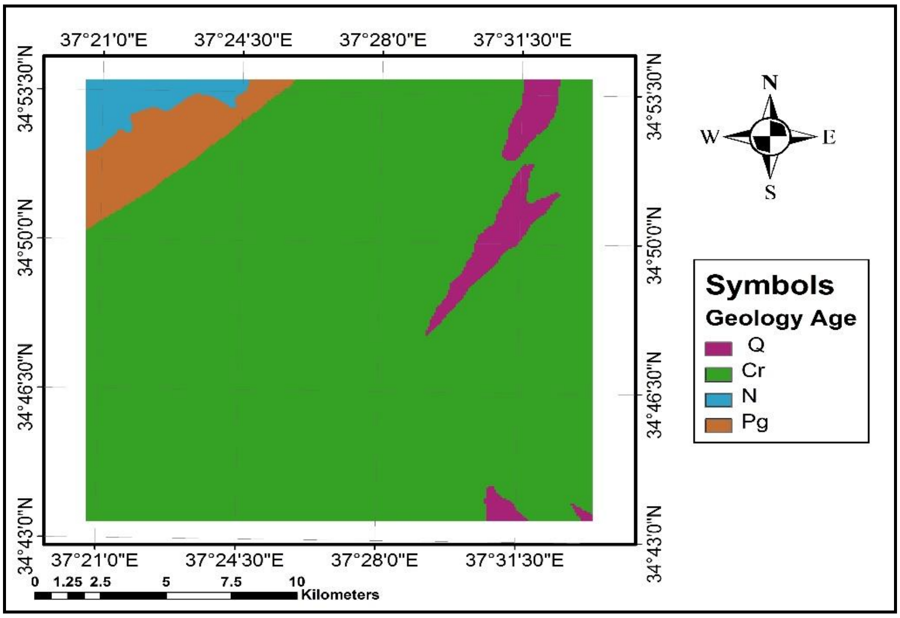

Figure (4): Geological map of the study area

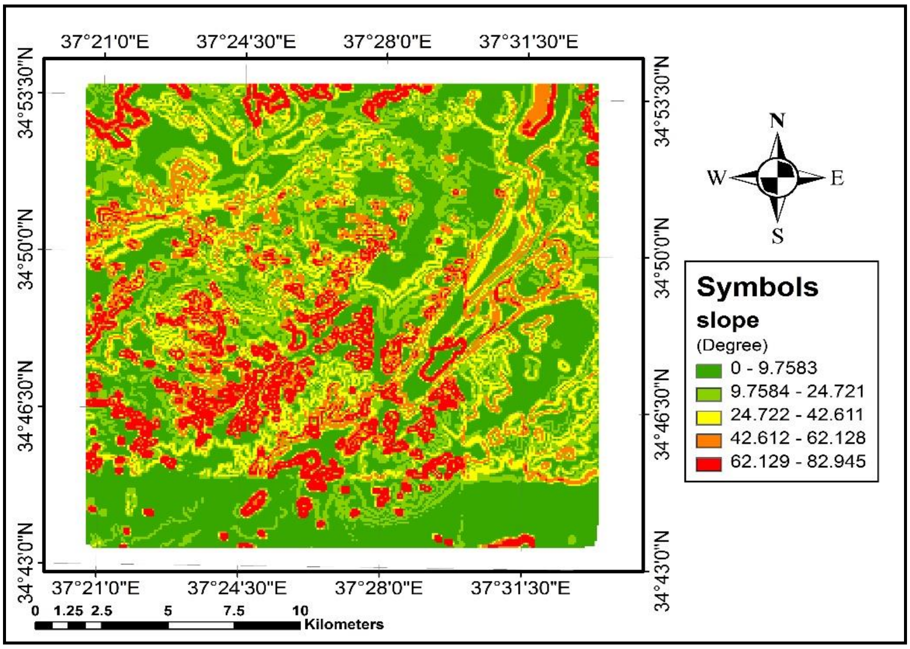

Figure (5): Distribution of Slope in the study area

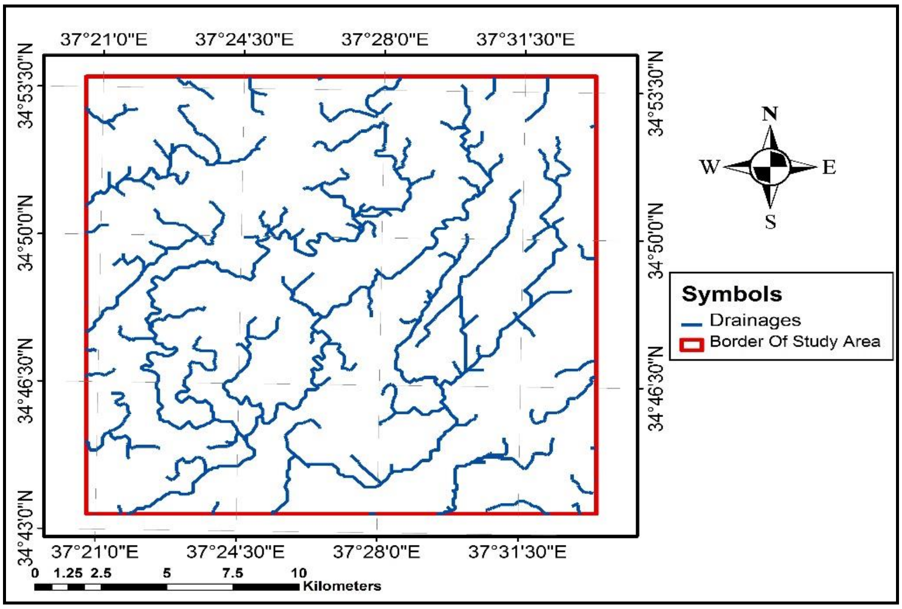

Figure (6): Distribution of the drainages network in the study area

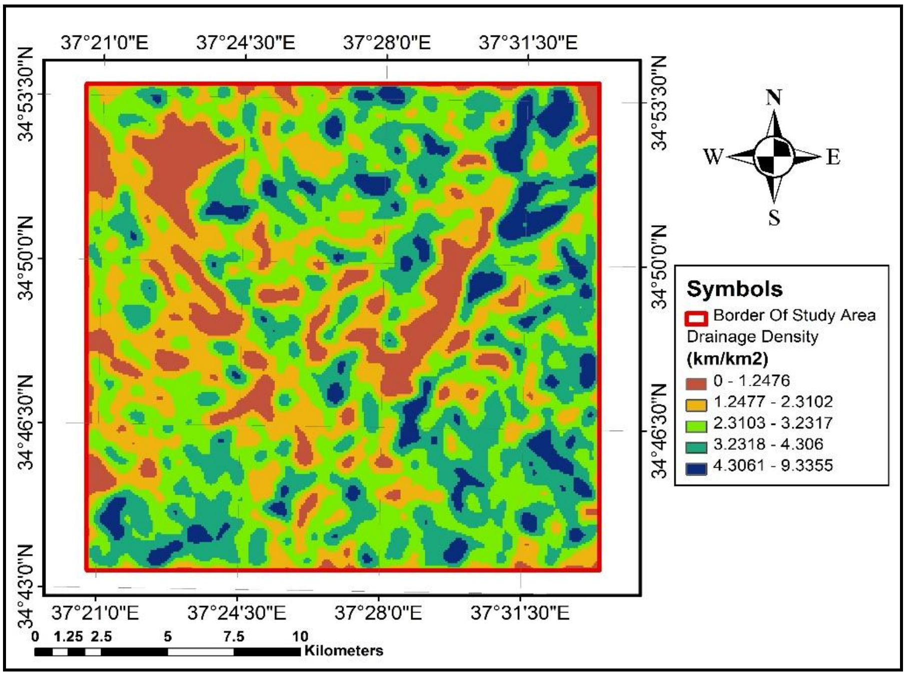

Figure (7): Drainage's density in the study area

Rainfall: Rainfall is a key source of nutrition and has an important influence on the identification of potential water harvesting sites and the effectiveness of the multi-criteria decision. We note that the study area has an annual rainfall of less than (200mm) as shown in Figure(3). .

Soil: Soil is one of the important factors that contribute to identifying potential water harvesting sites that affect runoff and infiltration rate, as soft soils that have the ability to retain water are more effective in water harvesting. Figure (8) shows the soil distribution chart in the study area, where the larger number indicates the soils that contribute the most to the water harvesting process.

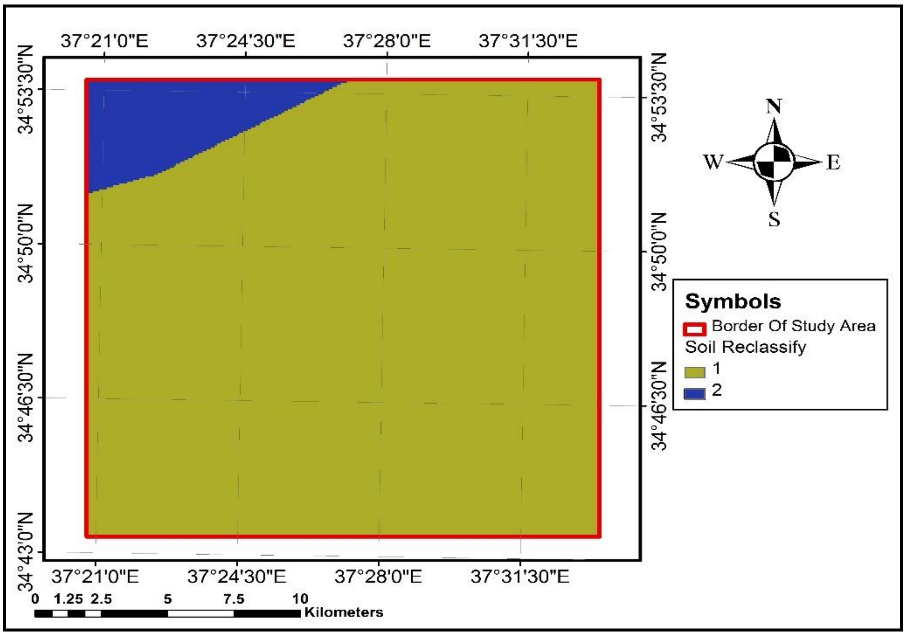

Figure (8): Distribution of soils in the study area

Calculate the distribution of potential water harvesting site

By applying the weights extracted from the hierarchical analysis method (AHP) to the slides and charts in the Geographic Information System (GIS) (flume density, geology, slope, rainfall, soil), the final chart was obtained for the distribution of the sectors of potential water harvesting sites in the study area, which were divided into three classes in terms of suitability, namely: Weak, medium, good, as shown in Figure (9) by using the weighted linear combination (WLC) technique

Si = (Rw.Rr) + (SLw.SLr) + (Sw.Sr) + :through the following equation [AL-HARBI, 2001]

where: W: represents the weight of each criterion (scale), r: represents the (DDw.DDr) + (Gw.Gr) rating for each criterion. (R): Rainfall, (SL): Slope, (S): Soil, (DD): Drainage density, (G): Geology (Si): A dimensionless number representing the number of sites suitable for water harvesting (Water Harvesting Manual).

Several environmental factors were also considered and excluded: Cities, faults, and wells. They were converted to Raster format in the GIS program and applying a sanctuary for these factors with a certain distance as shown in Table (10) and then applying the weighted linear combination technique in the GIS program to these factors with a sanctuary in the study area, i.e., the spatial techniques that were applied to these factors are: (calculator raster reclassification, union, buffering,). Thus, an unsuitability map was obtained to exclude sites that are not suitable for water harvesting. Figure (10) shows the study area with the excluded factors (faults, cities, wells). Figure (11) shows the study area after applying sanctuary to the excluded factors. Figure (12) shows the sites suitable for water harvesting after excluding unsuitable sites.

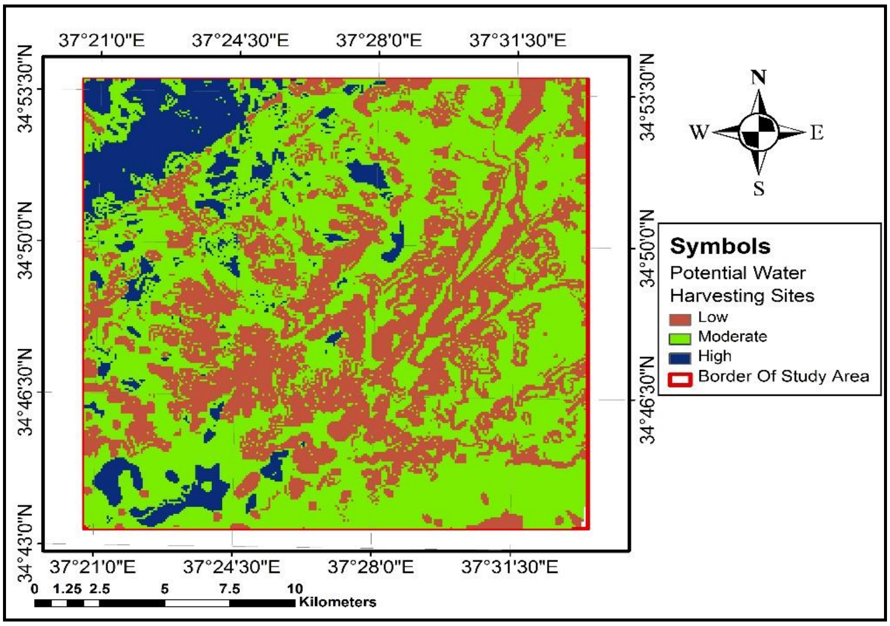

Figure (9): Potential water harvesting sites in the study area

Table (10): Campus of excluded factors in the study area [AL_damat, et al, 2010]

Name of the excluded factor	Wells	Cities	Faults
Distance(m)	500	250	1000

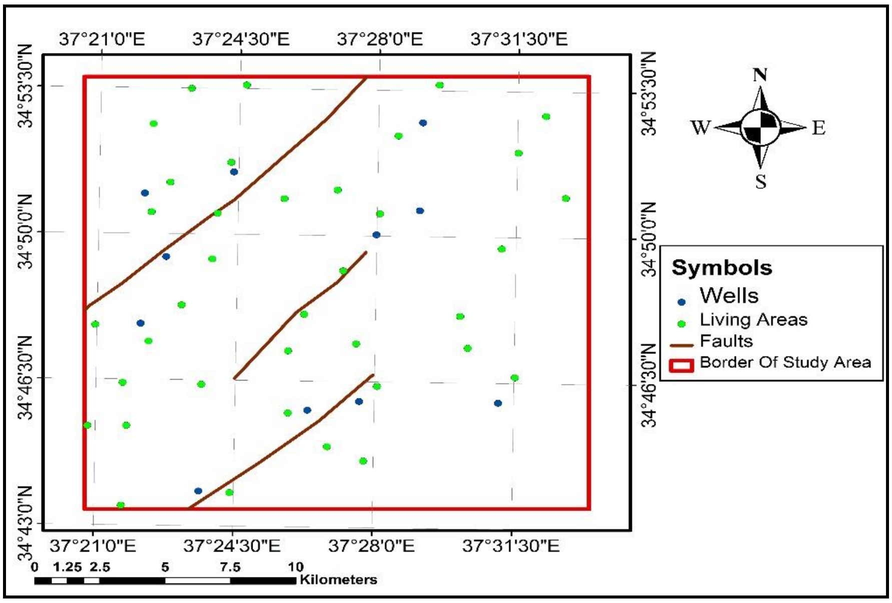

Figure (10): Excluded factors (Faults, cities, wells) in the study area

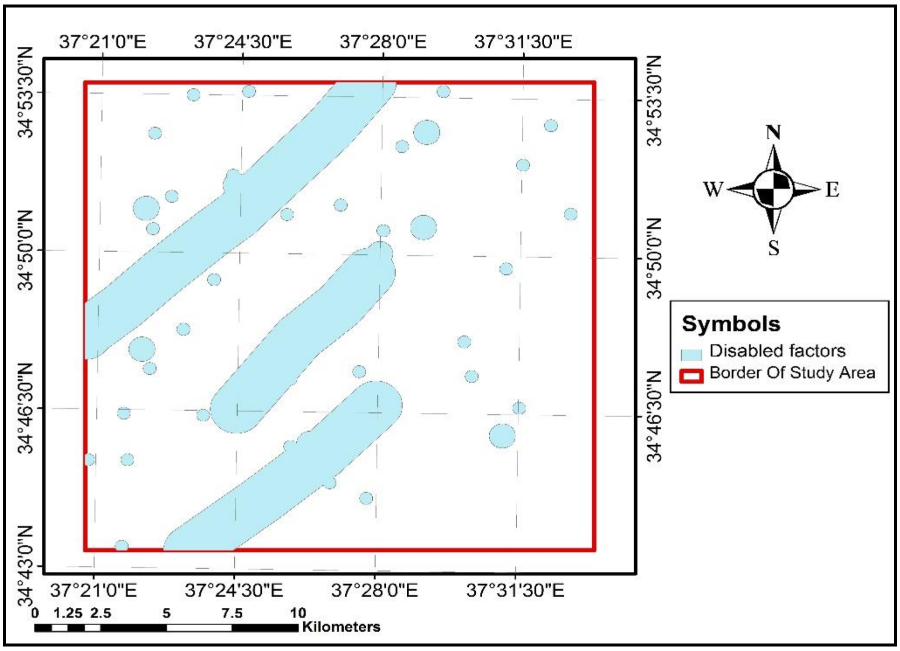

Figure (11): Applying a sanctuary to the excluded factors in the study area

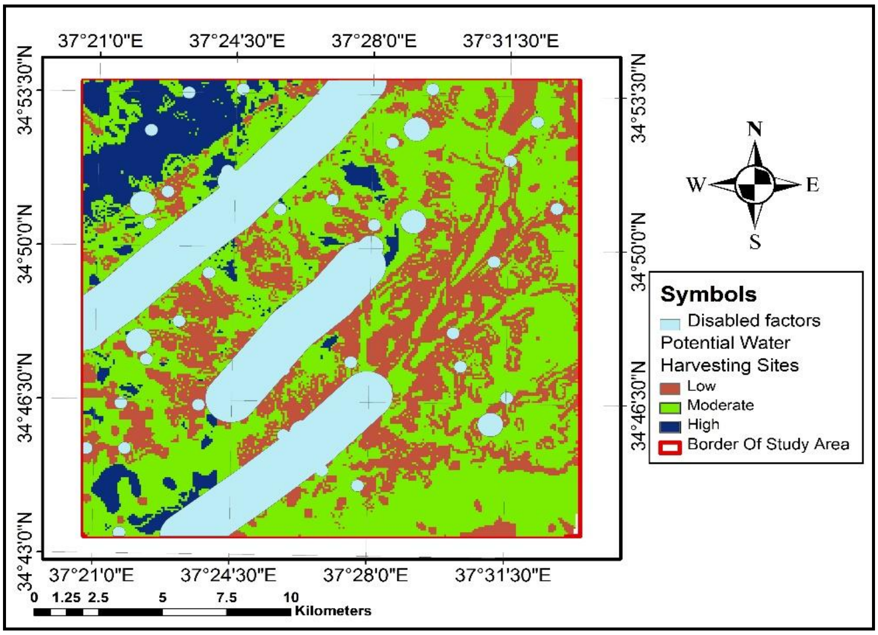

Figure (12): Suitable locations for water harvesting in the study area

Results and discussion:

In the studied area, the following were obtained :

1- low areas, representing 39.30% of the study area

2-Medium areas where it represents 40.55% of the study area

3- High areas where it represents 20.15% of the study area

Topographically, by comparing the suitability map for water harvesting with the slope map of the study area, it is observed that the sites with high water harvesting classification range from (24.72-42.61) degrees, while the sites with medium water harvesting classification range from (9.75-24.72) degrees. Hydrologically and hydrogeologically, we observe that the flume density in sites with high water harvesting classification ranges

between (3.23-4.30 km/km^2), which represents the highest value of flume density in the study area, while the flume density in sites with medium classification ranges between (2.31-3.23 km/km^2).
Geologically speaking, water harvesting sites must be located on solid ground and away from faults, and this is achieved in the study area, as water harvesting sites in sites with high to medium classification are in rock layers of geological age (Neogene and Paleogene) consisting of limestone, Ghadari, Ghadar and Marl. This confirms the logic of the results obtained. This shows the effectiveness of GIS techniques in accomplishing this type of studies, saving time, effort and money and presenting the decision-maker with a set of options based on a technical and scientific basis compared to traditional methods, especially in areas with different environmental, topographical and geological nature, where the higher priority sites are first directed to build dams on them.

Conclusions and recommendations:

Conclusions:

1. Adopting a new weighting methodology for the study area mathematically derived from the double comparison matrix of expert opinion, where the results showed the correctness of the weighting ratios assumed in the search based on the algorithm, when compared with the results of experts for similar areas by examining the match ratio of experts, where $CR \leq 0.1$.
2. The methodology used to identify potential water harvesting sites saves time and effort by reducing the search areas and limiting them to the highest priority area, thus supporting geophysical methods and contributing to strategizing and decision-making.

Recommendations:

1. Surveying suitable sites to verify that the sites are not occupied by high socio-economic land uses, this helps prevent the selection of these sites, which may be unknown to the researcher when conducting the site selection analysis .
2. Expanding the data by increasing the influencing factors to document their suitability in forming water harvesting sites, which leads to more accurate results.
3. The need to activate water basin management strategies in dry areas by building a conscious plan for the integrated management of surface and groundwater resources.

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