Groundwater Recharge Potential Assessment in Azraq Basin, Jordan Using Multi-Criteria Decision Making (MCDM) - GIS and Geophysical Techniques

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Abstract

This research aimed to determine the optimal locations for artificial groundwater recharge in the central Azraq Basin using geophysical methods and geographic information sciences. The study identified the eight most important criteria affecting the selection of artificial groundwater recharge sites in the area. Using the Analytic Hierarchy Process method, the study determined the weight of each criterion and established ratings based on available literature. GIS with Multiple Criteria Decision Analysis were used to select the most suitable sites for groundwater recharge, revealing that 5.7% of the study area has low suitability for groundwater recharge, 39.5% showed moderate, 46% showed high, while the remaining 8.8% of the study area showed very high suitability of groundwater recharge. The study employed the Electrical Resistivity Tomography geophysical survey method to verify the results. The ERT results showed that the groundwater level depth in the six examined sites was close to the subsurface level and ranged from 5m at ERT-2 (Basalt aquifer) to larger than 22m in ERT-4 (Rijam aquifer B4), indicating that these sites were suitable for groundwater recharge. ERT results also showed the presence of faulted layers and reveal the presence of favourable recharge zone. Overall, the study recommended that the area can be recognized as having a high potential for groundwater recharge, and projects should be developed accordingly. The research findings have important implications for managing and conserving water resources in arid regions. The study highlights the usefulness of geophysical methods and GIS in identifying and assessing suitable locations for artificial groundwater recharge. It also showed the importance of considering multiple criteria and using a structured decision-making approach in complex decision-making problems.

Keywords: GIS; Artificial groundwater recharge; Resistivity; Aquifer

1. Introduction

Jordan faces a severe water resource shortage in addition to its energy challenge. The country’s per capita share of water is one of the lowest ratios worldwide, having decreased in recent years to less than 100 cubic meters (Ministry of Water and Irrigation (MWI), 2016). The challenge is compounded by a high rate of population growth as the annual population growth rate in Jordan stands to 3.05% for 2023 (DOS, 2023) and the influx of refugees, including the long-standing influx of Palestinian refugees and the recent wave of over one million Syrian refugees residing in Jordan. Jordan’s water resources consist of surface water and groundwater. Surface water is obtained through dams and other water harvesting

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schemes resulting from rainfall ranging from 6 billion cubic meters (BCM) during dry years to 12 BCM in wet years (Al-Adamat, 2002). In arid and semi-arid regions, such as Jordan, groundwater is a crucial source of freshwater for domestic and agricultural purposes. Boreholes, hand-dug wells, and springs provide access to resources that are typically renewable, such as the Azraq groundwater aquifer system, or non-renewable, like the Disi Aquifer system (Adhikary et al., 2012).

The Azraq Basin, covering over 12,052 km², is situated in the North-central region of Jordan and is considered one of the country’s most vital water sources. Unfortunately, many of Jordan’s renewable groundwater resources are currently being exploited at or beyond their safe yield, which poses a significant risk to the long-term sustainability of these resources (Al-Adamat, 2002). For example, the Azraq aquifer system’s safe yield is approximately 25 MCM, yet it is currently utilized to the maximum capacity. Given the importance of groundwater in Jordan, it is essential to implement strategies to manage and improve its recharge using artificial groundwater methods. Artificial groundwater recharge refers to the process of increasing the amount of water that enters the aquifers through human-made methods (Bouwer, 2002; Bhattacharya, 2010). It can serve as a crucial tool for enhancing water resources, especially as population growth and per capita consumption continue to rise, leading to increased demand for water in the future (Kumari and Krishna, 2013). By identifying aquifers that bear groundwater and utilizing untapped water resources, artificial groundwater recharge can be a practical solution to address this challenge (Hammouri et al., 2014). Geophysical methods are utilized to obtain knowledge of the subsurface geophysical and geological characteristics and their spatial distribution, which enables horizontal and vertical delineation of subsurface strata and interpretation of the geological structure (Kneisel et al., 2008).

The Analytic Hierarchy Process (AHP) is a decision-making methodology developed by Thomas L. Saaty in the 1970s. The AHP is widely used in fields such as engineering, business, and management to make complex decisions that involve multiple criteria and alternatives. AHP combining with GIS and Remote sensing (RS) was used for mapping groundwater potential zones (Al-Gubri et al., 2023; Ramzi and Al-Gubri, 2022; Al-Gubri et al., 2022).

Geophysical investigation methods have achieved significant importance due to their non-invasive nature, reliability, and effectiveness. They are often more cost-effective than other methods, such as drilling, and are characterized by rapid field application and high-resolution data collection in a short time (e.g., Al Amoush and Mashagbeh, 2009). Combining Electrical Resistivity Tomography (ERT) with other geophysical techniques, such as electromagnetic and self-potential methods, has also been suggested as a non-invasive approach for investigating embankment conditions (Sentenac et al., 2013; Sentenac et al., 2017), geophysical methods have been used for geotechnical engineering applications (Ghanem et al., 2021). In addition, electrical resistivity methods have been successfully employed for exploring groundwater resources (Olorunfemi and Fasoyi, 1993; Olasehinde, 1999; Alile et al., 2008; Alrawi et al., 2023; Noon et al., 2023; Al-Hameedawi et al., 2022) and for groundwater artificial recharge studies (Al Amoush, 2006; Al Amoush, 2010; Al Amoush et al., 2015). GIS, MCDM and new technologies methods have been used extensively in groundwater recharge studies (Al-Shabeb et al., 2018; AlAyyash et al., 2023).

This study aims to determine the most vital criteria that affect the selection of artificial groundwater recharge sites in the study area using AHP-GIS, and the results will be validated by geophysical ERT methods.

2. Study area

The study area is located in the central part of the Azraq Basin. It surrounds the Azraq Oasis from the West, North, and East, and it lies between 36.740351° and 37.029926° E and 31.826109° to 31.931647° N. It has an area of 353.6 km² (Fig. 1). The area experiences a hot and dry climate during
summers and cold and wet weather in winters, with uneven high-intensity rainfall events of short duration. Additionally, the region witnesses high evaporation rates. This area was selected based on its proximity to the valleys that feed the ancient Azraq Oasis.

2.1. Geology

The Northern Badia region of Jordan is covered by basaltic lava, which covers an area of 11,103 km² and is part of a larger 45,103 km² lava (Al-Tarawneh, 1996; Allison et al., 1998). The basaltic eruptions are formed by feeder basalt dykes and consist of massive flows up to ten meters thick with a combined thickness of up to a hundred meters. According to Khalil (1993), it is amelanocratic, dark to medium grey, polycrystalline, medium to fine-grained, and porphyritic basalt. Its lithological description is characterized by the presence of vesicles and strong vertical and horizontal jointing that forms polygonal shapes. The joint spacing can reach 7 cm, especially in the upper part of the layers. The principal geological formations outcropped in the study area can be summarized as follows: Muwaqqar Chalk Marl formation and the Umm Rijam/Wadi Al-Shalala formations: They belong to the Balqa group; the Muwaqqar chalk marl formation extends from the upper Cretaceous to the lower Tertiary, with a thickness of up to 80–90 (Ibrahim, 1996). The Umm Rijam/Wadi Al-Shalala formation extends from the Paleocene to the Eocene, and it consists of successions of various types of limestone, marl, chalk, and flint (Ibrahim, 1996). Gravel, mudflat (Clay), Superficial and Pleistocene sediments (Gravel): they are composed mainly of stony boulder deposits with low ridges of gravel, silt, sand, and very fine sediments, clay, and basalt fragments. The superficial and wadi sediments are composed of stony boulders, unsorted angular to sub-angular gravels, small basalt boulders, sand, and silt of various lithological units and geological formations. They are derived from successive flooding events in the past that have flooded the main wadi. The Pleistocene deposits are exposed in the study area as an almost level gravel, plain, comprising angular, poorly sorted clasts mostly of a chert rock unit in a silty to sand matrix (Khalil, 1993). These poorly consolidated sediments consist mainly of up to 15 m thick level strewn plain and are lateral terraces to present-day drainage. When Al Azraq Lake was larger than now, alluvial fans and braided stream sediments were deposited periphery of the lake (Ibrahim, 1996). Fig. 2 shows the main geological rock units in the study area (Bender, 1974).

![Fig. 1. Study area.](image-url)
3. Materials and Methods

3.1. Groundwater Recharge Influencing Criteria

Previous studies have identified eight essential criteria for choosing suitable sites for groundwater recharge. These criteria include groundwater depth, geology, land use, slope, soil type, lineament density, rainfall, and drainage density. Each criterion plays a crucial role in determining the suitability of an area for groundwater recharge. Table 1 provides some explanations of these criteria.

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Importance</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainfall</td>
<td>It is the primary factor in selecting sites for groundwater recharge.</td>
<td>Anbazhagan et al. (2005); Al-Adamat et al. (2010); Juaidi, 2008; Machiwal et al. (2011).</td>
</tr>
<tr>
<td>Land use/cover</td>
<td>Different land use/ land cover influence the possibilities of groundwater recharge.</td>
<td>Chowdhury et al. (2010); Sargaonkar et al. (2011).</td>
</tr>
<tr>
<td>The groundwater depth</td>
<td>The depth to the water table is a vital factor in identifying appropriate locations for groundwater recharge since it indicates the distance between the ground surface and the groundwater level.</td>
<td>Ghayoumian et al. (2005); Machiwal et al. (2011).</td>
</tr>
<tr>
<td>Slope</td>
<td>Lower slope areas are more likely to recharge groundwater than steeper slopes. Various studies have demonstrated that slope is pivotal in determining the appropriate sites for groundwater recharge.</td>
<td>Saraf and Choudhury (1998); Chowdhury et al. (2009); Chowdhury et al. (2010); Valliammaiet al. (2013); Hammouri et al. (2014).</td>
</tr>
</tbody>
</table>
Lineament density: In basaltic regions, fractures and joints serve as conduits for water movement to the aquifer, thus making lineament density a particularly significant factor. Previous research has demonstrated that lineament density is essential for selecting appropriate groundwater recharge sites. Balachandar et al. (2010); Valliammai et al. (2013)

Drainage density: Drainage density is a crucial consideration as it is an indirect indicator of areas with high permeability and surface runoff conducive to groundwater recharge. Ghayoumian et al., (2007); Chowdhury et al. (2010)

Soil: Soil directly influences water infiltration capacity. Soils with high porosity, such as sandy soils, have a greater capacity for infiltration than soils with lower porosity, such as heavy clay or loamy soils. Therefore, the porosity of the soil is a critical factor to consider when determining the appropriateness of a site for groundwater recharge. Al-Adamat, (2008); Sargaonkar et al. (2011);

Geology: Geological formations characterized by high porosity, permeability, and numerous cracks and fractures are suitable for establishing groundwater recharge sites. Therefore, these factors play a significant role in identifying appropriate locations for groundwater recharge. Torabi-Kavehet al. (2016)

Fig. 3 illustrates that the elevation within the study area varies from 485 m a.s.l in the southeastern parts to 595 m a.s.l in the northern parts. This is translated into that most of the study area has a gentle slope of less than 6% (Fig. 4). The study area comprises two soil textures: loam in the northern parts and sandy loam in the south, as depicted in Fig. 5. The drainage network in the study area, which consists of several Wadis flowing towards the Azraq Oasis from the north, northwest, and northeast, is illustrated in Fig. 6. Additionally, Fig. 7 shows that the lineament in the area comprises several lines with an NW-SE trend. The study area contains three major land uses/cover: bare soil and rocks, agriculture, and urban, as indicated in Fig. 8. Finally, Fig. 9 reveals that the depth to the groundwater in the study area varies from less than 5 m in the southern parts to more than 16 m in the northern parts.

Fig. 3. Elevations within the study area in meters (USGS ASTER DEM). Fig. 4. Slope in the study area (Based on SRTM DEM).
3.2 Data Collection

The methodology adopted in this study is summarized in the flowchart depicted in Fig. 10. The geospatial data of eight parameters used in this study were gathered from various sources. Table 2 lists the types and sources of data used.

3.3. Analytic Hierarchy Process (AHP)

The AHP breaks down complex decision-making problems into smaller, more convenient parts, permitting decision-makers to make informed and realistic alternatives. It involves creating a hierarchical model of the decision-making problem, with the decision criteria at the top level and the alternatives at the bottom level. The criteria are then paired, and the decision-maker allocates weights
to each criterion based on their relative significance. This procedure is repeated for each level of the hierarchy until a final decision is achieved (Saaty and Vargas, 2012; Triantaphyllou, 2000; Saaty, 1980).

![Flowchart showing the methodology used in this study.](image)

**Fig. 10.** Flowchart showing the methodology used in this study.

**Table 2.** Types and sources of primary and secondary data used in the study.

<table>
<thead>
<tr>
<th>Data type</th>
<th>Data</th>
<th>Scale/ Resolution</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Secondary data</td>
<td>Rainfall</td>
<td>1:250,000</td>
<td>Al-Adamat et al. (2007)</td>
</tr>
<tr>
<td></td>
<td>Soil</td>
<td>1:250,000</td>
<td>Jordan Ministry of Agriculture</td>
</tr>
<tr>
<td></td>
<td>Geology</td>
<td>1:250,000</td>
<td>Natural Resources Authority (2008)</td>
</tr>
<tr>
<td></td>
<td>Drainage Density</td>
<td>1:250,000</td>
<td>Natural Resources Authority (2008)</td>
</tr>
<tr>
<td></td>
<td>Slope</td>
<td>1:250,000</td>
<td>Natural Resources Authority (2008)</td>
</tr>
<tr>
<td></td>
<td>Well data</td>
<td>1:250,000</td>
<td>Natural Resources Authority (2008)</td>
</tr>
<tr>
<td></td>
<td>Lineament</td>
<td>1:250,000</td>
<td>Natural Resources Authority (2008)</td>
</tr>
<tr>
<td></td>
<td>Lineament Density</td>
<td>1:250,000</td>
<td>Natural Resources Authority (2008)</td>
</tr>
<tr>
<td>Primary data</td>
<td>Land use/cover</td>
<td>30 m</td>
<td>Extracted from SRTM DEM (USGS)</td>
</tr>
<tr>
<td></td>
<td>ERT Geophysics</td>
<td>30 m</td>
<td>Extracted from SRTM DEM (USGS)</td>
</tr>
<tr>
<td></td>
<td>ERT</td>
<td>4 m</td>
<td>Extracted from SRTM DEM (USGS)</td>
</tr>
<tr>
<td></td>
<td>ERT Profiles</td>
<td>4 m</td>
<td>Extracted from SRTM DEM (USGS)</td>
</tr>
</tbody>
</table>

One of the strengths of the AHP is that it allows decision-makers to include quantitative and qualitative data into the decision-making process. This is accomplished through pairwise comparisons, where decision-makers compare each criterion or alternative to every other one. These comparisons are then used to calculate relative weights, which are used to make the final decision. Another benefit of the AHP is that it can be used to recognize irregularities or errors in the decision-making process. The pairwise comparisons are verified for consistency using a mathematical formula, and any inconsistencies are marked for review. This allows decision-makers to identify and correct errors or inconsistencies in their decision-making process (Saaty and Vargas, 2012; Triantaphyllou, 2000; Saaty, 1980).

To carry out this research, important criteria were identified for selecting the best sites to recharge groundwater, and appropriate weights were assigned to these criteria based on a review of available literature on selecting suitable sites for groundwater recharge. The Analytic Hierarchy Process (AHP) was applied to determine whether expert opinions (cited literature) consistently used the pairwise comparison method (PCM). The computation of relative weights relied on the methods proposed by Malczewski (1999) and Saaty (1990), which involved:

- Aggregating the values in each column of the pairwise comparison matrix.
- Dividing each element in the pairwise comparison matrix by the total of its respective column.
Computing the mean of the elements in each row of the pairwise comparison matrix (normalizing inputs).

The estimation of the consistency ratio (CR) involves the following operations (Malczewski, 1999; Saaty, 1990):

- Computing $\lambda_{\text{max}}$ (The Principal Eigenvalue): The value of $\lambda_{\text{max}}$ is the average number of the consistency vector (Malczewski, 1999; Saaty, 1990). The calculation of $\lambda_{\text{max}}$ is the sum of the consistency vectors divided by the number of the consistency vectors.

$$\lambda_{\text{max}}= {1/n\sum n/ = 1(A.W/W)}$$

Where $A$ is known as the judgment matrix and $n$ is the order of the matrix. $A.W$ is the sum of the weight vectors and the $A.W/W$ is the consistency vector. The eigenvalue ($\lambda_{\text{max}}$) must always be greater than or equal to the number of the criteria ($n$) for a positive value and $\lambda_{\text{max}} = n$ if the pairwise comparison matrix is a consistent matrix. If there is any inconsistency in the experts' opinions, a difference between $n$ and $\lambda_{\text{max}}$ is indicated. Therefore, $\lambda_{\text{max}} - n$ can be classed as a measure of the degree of inconsistency.

- Computing the Consistency index (CI): The calculation of CI is based on the observation of $\lambda_{\text{max}}$. As it is in the following equation (Saaty, 1990; Malczewski, 1999):

$$CI= (\lambda_{\text{max}} - n) / (n-1)$$

- Determining the appropriate value of the random consistency ratio (RI): The random index (RI) is the consistency index of a randomly generated pairwise comparison matrix (Saaty, 1977 Saaty, 1990). RI depends on the number of criteria being compared, as shown in Table 3 (Saaty, 1980). The weighted sum vector is computed by multiplying each criterion's weight by the sum of its associated column of the pairwise comparison matrix, then summing the acquired values of each row.

- Calculating the Consistency Ratio (CR): The consistency ratio is given in the following equation:

$$CR= CI/RI$$

**Table 3.** Average random consistency indices (RI) for different numbers of criteria, adapted from Saaty (1980).

<table>
<thead>
<tr>
<th>Number of Criteria</th>
<th>Random Consistent Indices (RI)</th>
<th>Number of Criteria</th>
<th>Random Consistent Indices (RI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>9</td>
<td>1.45</td>
</tr>
<tr>
<td>2</td>
<td>0.0</td>
<td>10</td>
<td>1.49</td>
</tr>
<tr>
<td>3</td>
<td>0.58</td>
<td>11</td>
<td>1.51</td>
</tr>
<tr>
<td>4</td>
<td>0.90</td>
<td>12</td>
<td>1.54</td>
</tr>
<tr>
<td>5</td>
<td>1.12</td>
<td>13</td>
<td>1.56</td>
</tr>
<tr>
<td>6</td>
<td>1.24</td>
<td>14</td>
<td>1.57</td>
</tr>
<tr>
<td>7</td>
<td>1.32</td>
<td>15</td>
<td>1.59</td>
</tr>
<tr>
<td>8</td>
<td>1.41</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4 lists the pairwise comparison matrix for expert opinion's on the selection criteria of groundwater recharge. The pairwise comparison found that $\lambda_{\text{max}}$ is 8.00 CI is 0.000721, RI is 1.14, and CR is 0.000511 for the study area criteria analysis. Based on that, the weights for all layers were calculated as listed in Table 5. This table also provides the ratings for each layer based on the cited literature.
3.4.1. Introduction

The resistivity survey method is one of the oldest and most popular geophysical exploration methods. It is used in different engineering, environmental and mining applications (e.g. Reynolds, 2011; Chambers et al. 2006; Dahlin, 2001, Dahlin et al. 2002; Rucker et al. 2010; Kuras et al. 2007), hydrology and surface water applications (Page, 1968, Wilson et al. 2006), groundwater exploration (Seaton and Burbey 2000), archeology (e.g. Griffiths and Barker, 1993; Tsokas et al. 2008), lithology, degree of saturation, and composition of pure water (e.g. Lesmes and Friedman, 2005; Al-Amoush et al. 2017), and mineral exploration surveys. Besides surface surveys, it has been used across wells (Chambers et al. 2003, Daily and Owen, 1991). Two-dimensional resistivity surveys are widely performed, and even three-dimensional surveys are becoming more common in areas of very complex geological settings (Dahlin 2001; Auken et al. 2006; Chambers et al. 2006). Resistivity is a measure of opposition to an object's electric current flow. The resistivity of a soil or rock depends on several factors, including the

| Table 4. The pairwise comparison matrix of expert options. |
|-----------------|--------|--------|--------|--------|--------|--------|--------|--------|
| R.A. 8          | 1      | 1.3333 | 1.6000 | 1.6000 | 2      | 2.6667 | 4      | 8      |
| LU 6            | 0.7500 | 1      | 1.2000 | 1.2000 | 1.5    | 2.0000 | 3      | 6      |
| DG 5            | 0.6250 | 0.8333 | 1      | 1.0000 | 1.25   | 1.6667 | 2.5    | 5      |
| S.P. 5          | 0.6250 | 0.8333 | 1      | 1      | 1.25   | 1.6667 | 2.5    | 4      |
| L.D. 4          | 0.5000 | 0.6667 | 0.8    | 0.8    | 1      | 1.3333 | 2      | 4      |
| D.D. 3          | 0.3750 | 0.5000 | 0.6    | 0.6    | 0.75   | 1      | 1.5    | 3      |
| SO 2            | 0.2500 | 0.3333 | 0.4000 | 0.4    | 0.5    | 0.6667 | 1      | 2      |
| GY 1            | 0.1250 | 0.1667 | 0.2000 | 0.25   | 0.25   | 0.3333 | 0.5    | 1      |
| SUM 4.25        | 5.6667 | 6.8    | 6.85   | 8.5    | 11.3333 | 17    | 33     |

LD: Lineament Density; DG: Depth to Groundwater; SP: Slope; GY: Geology; SO: Soil; RA: Rainfall; LU: Land use/ Cover; DD: Drainage Density

| Table 5. Weights and Ratings for the selection criteria |
|-----------------|--------|--------|--------|--------|--------|--------|--------|--------|
| Criterion (Weight) | R.A. (0.24) | L.U. (0.18) | DG (0.15) | S.P. (0.14) | L.D. (0.12) | D.D. (0.09) | SO (0.06) | G.Y. (0.03) |
| Characteristic    | Mm     | Class  | m     | %     | km/ km² | km/ km² | Texture | Type     |
| Vegetation        | 0-05   | 01-06  | >3.5  | 0-0.75 |
| Agriculture       | 06-11  | 07-16  | 2.5-3.5 | 0.75-1.5 |
| Waterbody         | 12-16  | 17 - 26 | 1.5-2.5 | 1.5-2.25 |
| Urban             | > 16   | > 26   | 0-1.5  | > 2.25  |
| Sandy Loam        |        |        |        |        |
| Loam              |        |        |        |        |
| Soil              |        |        |        |        |
| Rock              |        |        |        |        |
| Clay              |        |        |        |        |
| Limestone         |        |        |        |        |
| RA: Rainfall; LU: Land use/ Cover; DG: Depth to Groundwater; SP: Slope; LD: Lineament Density; DD: Drainage Density; SO: Soil; GY: Geology

3.4. Electrical Resistivity Method

The resistivity survey method is one of the oldest and most popular geophysical exploration methods. It is used in different engineering, environmental and mining applications (e.g. Reynolds, 2011; Chambers et al. 2006; Dahlin, 2001, Dahlin et al. 2002; Rucker et al. 2010; Kuras et al. 2007), hydrology and surface water applications (Page, 1968, Wilson et al. 2006), groundwater exploration (Seaton and Burbey 2000), archeology (e.g. Griffiths and Barker, 1993; Tsokas et al. 2008), lithology, degree of saturation, and composition of pure water (e.g. Lesmes and Friedman, 2005; Al-Amoush et al. 2017), and mineral exploration surveys. Besides surface surveys, it has been used across wells (Chambers et al. 2003, Daily and Owen, 1991). Two-dimensional resistivity surveys are widely performed, and even three-dimensional surveys are becoming more common in areas of very complex geological settings (Dahlin 2001; Auken et al. 2006; Chambers et al. 2006). Resistivity is a measure of opposition to an object's electric current flow. The resistivity of a soil or rock depends on several factors, including the
amount of interconnected pore water, porosity, total dissolved solid (TDS) such as salts, mineral and chemical composition, Saturation degree, Depth, and age of the rock. Two-dimensional electrical resistivity tomography (2D ERT) surveys were conducted at six sites selected as suitable sites for groundwater recharge in Azraq Basin. Table 6 lists each ERT section’s coordinates, elevation, and strike, and Fig. 19 shows the location map of ERT’s.

### 3.4.2 ERT data collection, processing and modeling

The 2-D Electrical resistivity tomography surveys were performed with profile lengths of 240m using a multi-channel system containing 48 electrodes. The spacing between every two adjacent electrodes was 5m. The multi-channel system automatically operates once identify the type of electrical configuration and geometrical parameters. The Field electrical resistivity measurements were taken by a SYSCAL Junior Switch Ohmmeter (IRIS Instruments, France). Electrical resistivity tomography (ERT) commonly uses 24 or more electrodes attached to a multi-core cable (Griffiths and Barker, 1994; Reynolds, 2011). Resistivity measurements are recorded and saved in the SYSCAL resistivity meter device automatically. The sequence of measurements, for example, electric current duration, survey parameter, and type of configuration, can be set up manually in the field or preliminary prepared and uploaded to the laptop microprocessor. ELECTRE PRO software was utilized to produce and create the measurement sequence for the field data collection (Al-Amoush et al. 2017). PROSYS II attached software was used to access, edit and filter the saved data after completion of the field survey, and RES2DINV modeling software was used to produce the inverted resistivity sections (Loke, 2014a).

In this study, six ERT profiles have been conducted. The locations of ERT profile were determined based on the final suitability map of groundwater artificial recharge map. The coordinates, elevations, ERT’s length and their strike direction were listed in Table 6. The main objective of the ERT method is to investigate and validate the selected sites chosen as suitable sites for groundwater recharge by MCDM-GIS modeling.

**Table 6. Coordinates, elevation, and strike of ERT sections.**

<table>
<thead>
<tr>
<th>#ERT</th>
<th>E (Longitude)</th>
<th>N (Latitude)</th>
<th>Elevation(masl)</th>
<th>ERT’s Profile Length</th>
<th>Strike</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERT1</td>
<td>36.825320°</td>
<td>31.922443°</td>
<td>533</td>
<td>240m</td>
<td>NW-SE</td>
</tr>
<tr>
<td>ERT2</td>
<td>36.856240°</td>
<td>31.926636°</td>
<td>561</td>
<td>240m</td>
<td>NW-SE</td>
</tr>
<tr>
<td>ERT3</td>
<td>36.710500°</td>
<td>31.859088°</td>
<td>570</td>
<td>240m</td>
<td>S-N</td>
</tr>
<tr>
<td>ERT4</td>
<td>36.732796°</td>
<td>31.919445°</td>
<td>543</td>
<td>240m</td>
<td>S-N</td>
</tr>
<tr>
<td>ERT5</td>
<td>36.732723°</td>
<td>31.829275°</td>
<td>546</td>
<td>240m</td>
<td>SE-NW</td>
</tr>
<tr>
<td>ERT6</td>
<td>36.876728°</td>
<td>31.874955°</td>
<td>512</td>
<td>240m</td>
<td>W-E</td>
</tr>
</tbody>
</table>

### 4. Results and Discussions

#### 4.1. GIS Data Analysis and Results

Eight criteria (Table 5) were analyzed in the GIS environment based on the methodology illustrated in Fig. 10. The annual precipitation values were assigned to a single rainfall category for the entire study area, which ranged from 50-100 mm/year, and weighted by a rating of 0.48. Table 5. Agriculture, urban, and bare soil/rock land use/cover types were assigned different weights based on their potential for groundwater recharge, and the resulting weighted land use/cover map shown in Fig. 11 ranges between 0.18 and 0.54.
The study area’s groundwater depth was classified into four categories, and areas with depths of \(\leq 5\) meters were considered highly suitable for groundwater recharge. Conversely, areas with depths of 6 - 11 meters were moderately suitable, 12-16 meters were low, and more than 16 meters were very low. The weighted depth to groundwater map (Fig. 12) ranges from 0.15 to 0.60.

Based on the slope range of 0 - 25% in the study area, three slope classes were identified: 0-6%, 6-16%, and 16-25%. Areas with a slope of 0-6% were considered highly suitable, 6-16% were moderately suitable, and 16-25% were very low regarding groundwater recharge potential. The resulting slope (weight \(\times\) ratings) map ranges from 0.28 to 0.56, as depicted in Fig.13.

Lineament density was categorized into four classes (high, moderate, low, and very low) based on Table (5), and the resulting lineament density (weight \(\times\) ratings) ranges from 0.092 to 0.368, as shown in Fig.14. Drainage density was classified into four categories (high, medium, low, and very low) based on Table 5, and high weight was assigned to regions with low drainage density, while low weight was assigned to regions with high drainage density. The resulting drainage density (weight \(\times\) ratings) map ranges from 0.09 to 0.36, as shown in Fig. 15.

The study area’s soil texture was classified into high (sandy loam) and low (clay or loam), with sandy loam soils being suitable for groundwater recharge. The resulting soil (weight \(\times\) ratings) map has two values of 0.64 and 0.256 (Fig. 16). Geology was classified into four categories (high, moderate, low, and very low), and the resulting geology (weight \(\times\) ratings) map ranges from 0.06 to 0.24, as shown in Fig.17.

Figs. 11 - 17 were combined using the Raster Calculator tool in ArcGIS, with a constant weight of 0.48 reflecting rainfall. The output map was categorized into suitable and unsuitable, based on Table 5. Cells with a value of two or more in the final map were considered appropriate for groundwater recharge. According to Table 7, the study area has low suitable area for groundwater recharge of 20.2 km², which accounts for 5.7% of the total area, moderate suitable for groundwater recharge of 139 km², account for 39% of the study area and show 193.3 km² high to very high suitable which account for 55% of the study area. Fig. 18 demonstrates the final categorized map.
Fig. 13. Slope (Weight $\times$ Ratings)

Fig. 14. Lineament density (Weight $\times$ Ratings)

Fig. 15. Drainage density (Weight $\times$ Ratings)

Fig. 16. Soil (Weight $\times$ Ratings)

Fig. 17. Geology (Weight $\times$ Ratings)

Fig. 18. Groundwater recharge suitability map
Table 7. Groundwater recharge suitability

<table>
<thead>
<tr>
<th>Suitability</th>
<th>Area (km²)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>20.2</td>
<td>5.7</td>
</tr>
<tr>
<td>Moderate</td>
<td>139.56</td>
<td>39.5</td>
</tr>
<tr>
<td>High</td>
<td>162.83</td>
<td>46.0</td>
</tr>
<tr>
<td>Very High</td>
<td>31.0</td>
<td>8.8</td>
</tr>
<tr>
<td>Sum</td>
<td>353.6</td>
<td>100</td>
</tr>
</tbody>
</table>

4.2. Resistivity - Lithology Correlation

Fig. 19 shows a location map of ERT geophysical survey sites in the study area. ERT’s sites were selected at different classes of groundwater recharge suitability based on the GIS-MCDA modeling results (Fig. 18) to validate the modeling results.

![Location map of ERT geophysical survey sites overlay the Suitability map for groundwater recharge](image)

Fig. 19. Location map of ERT geophysical survey sites overlay the Suitability map for groundwater recharge

In order to make a reliable and reasonable geological and hydro-geological interpretation of the ERT’s tomograms, several well logs data were used for correlation with the results of ERT's models. The information from logs F1043 and F1038 wells were correlated with ERT-1 tomogram. The log of F1171 well was correlated with ERT-3 tomogram and the log from F1155 well was correlated with ERT-4. The results of the correlation are shown on the associated tomograms. Fig. 20 and Fig. 21 show lithological hydro-geological cross sections deduced from the well log information.
Fig. 20. N-S Lithological correlations of wells (F1226, F1155, F1169, and F1179), showing the location of ERT-4, ERT-3 and ERT-5, and the depth to groundwater level.

Fig. 21. WSW–ENE Lithological correlations of wells (F1226, F1043), showing the location of ERT-4, ERT-1, and the depth to groundwater level.

4.3 Interpretation of ERT’s Tomograms

4.3.1. Electrical resistivity tomography (ERT-1)

ERT-1 extends in a NW–SE direction (Fig. 22). The resistivity distribution shows three principle geo-electric subsurface layers. The first layer has low resistivity values (2-20) Ohm.m with 7m thick. The second layer has higher resistivity values (70-150) Ohm.m and 20m thick. The third substratum layer has resistivity in the range of (150-300) Ohm.m. A correlation of the inverted ERT-1 with F1043 well log located at 300 m to the NW of ERT-1 has been made (Fig. 23). Identifying the static water level, which was 7m to 12m below the ground surface, was very helpful. Basalt rock units are the main aquifer at this site. The section exhibits a lateral structural fault in the second layer (Fig. 22).

4.3.2. Electrical resistivity tomography (ERT-2)

The ERT-2 extends in a NW–SE direction (Fig. 23). The resistivity distribution shows two principle geo-electric subsurface layers. The first layer has low resistivity values (1-40) Ohm.m, 5-20m thick which could be interpreted as a topsoil alluvium –alluvium mudflat layer. The second layer has high resistivity values 150 - 3000 Ohm.m and 28m thick. It characterized by high lateral structural
variations. The depth to water level as deduced from the water level map in the study area (Fig. 9) indicated a 5m depth which is correlated with variations in resistivity values at this depth. Basalt rock unit form the main aquifer at this site.

4.3.3. Electrical resistivity tomography (ERT-3)

The ERT-3 extends in an N-S direction (Fig. 24). The resistivity distribution shows two principal geo-electric subsurface layers. The first layer has low resistivity values (9 - 40) Ohm.m and is 9 - 11m thick. The second layer has high resistivity values (50-200) Ohm.m and 22m thick, and it characterized by lateral structural and or lithological variations. A correlation between the inverted model (ERT-3) with the well log F1171 located at (1.6 km. The groundwater level was found at 10m depth (Figure 9). The second layer correlated with marls, Chert of Rijam formation (B4). Lateral resistivity variations attributed to structural and/or lithological variations. The lithological units in F1169 located at a distance of 3.8 km to the NE indicated the presence of Chert, chalky limestone, which belongs to the Rijam formation (B4).

4.3.4. Electrical resistivity tomography (ERT-4)

The ERT-4 extends in an N-S direction (Fig. 25). The resistivity distribution shows an inhomogeneous subsurface layering. Resistivity values range from less than 2 Ohm.m to 220 Ohm.m. A correlation between the inverted model of ERT-4 (Fig. 25) and the well logs F1155 and F1226 has been made. The results show that the depth to groundwater is 20 m, and the main aquifer system in the study area is Rijam Formation (B4), represented as a Chert, marl. Zones of low resistivity values have been identified, which could be attributed to saturated substratum as favorable potential recharge zones.

4.3.5. Electrical resistivity tomography (ERT-5)

The ERT-5 extends in an SE-NW direction (Fig. 26). The resistivity distribution shows an inhomogeneous subsurface layer. The first geo-electrica layer has higher resistivity values (100-200) Ohm.m with around 12m thick. The second layer with lower resistivity values (1-80) Ohm.m. The depth to groundwater level, as correlated with the water level map (Fig. 9), is 12-14m. This is correlated with variations in resistivity values at this depth Fig. 26. Possible recharge zones (resistivity less than 10 Ohm.m) are identified in the eastern part of the tomogram.

4.3.6. Electrical Resistivity Tomography (ERT-6)

The ERT-6 extends in a W-E direction (Fig. 27). The resistivity distribution shows a homogenous three principle geo-electric subsurface layers. The first layer has low resistivity values (1-40) Ohm.m and 7m thick. The second layer has higher resistivity values (2 - 5) Ohm.m and 18m thick. The third subsurface geo-electric layer has (15-40) Ohm.m with unknown thickness.

Fig. 22. 2-D inverted resistivity model of ERT-1
5. Conclusions

This study aimed to select the best sites for groundwater recharge in the northern part of Azraq Basin in Jordan by making a map showing the most appropriate sites, and this is done by relying on
(MCDA) and (AHP) within Geographic information systems (GIS) and validating by electrical resistivity tomography-geophysical methods.

The study utilized selection criteria consisting of the slope, lineament density, soil type, drainage density, depth to groundwater, land use/cover, geology, and rainfall, which were chosen based on previous research. These factors were then used to generate a final map indicating the most suitable sites for groundwater recharge within the study area. To create a map of the most suitable sites for groundwater recharge, this study utilized the geographic information system's method of collecting weights and ratings for each criterion. Each criterion's ranking and weighting were determined to assess their relative importance in selecting the most appropriate sites. Using the chosen selection criteria and ranking information, a final map of suitable sites for groundwater recharge in the northern part of Azraq Basin was produced, as discussed in chapter four. The map was divided into two classes: suitable and not suitable for groundwater recharge.

In addition to GIS methods, the study employed the Electrical Resistivity Tomography (ERT) geophysical survey method to verify the results. Six different sites were examined, and the results were calibrated using geological data obtained from available groundwater well records to assess the potential for groundwater recharge in the selected locations. The outcomes of this study are as follows:

- A significant correlation was observed between the results of the Electrical Resistivity Tomography (ERT) and the Geographic Information System (GIS), indicating that all geophysical survey sites were suitable for conducting fieldwork.
- A high correlation was found between the ERT results and the subsurface layer characteristics in terms of thicknesses, rock type, and type of aquifer derived from geological log data.
- The ERT results allowed for identifying layer boundaries and concluding some geological structures, such as faults.
- The ERT results showed that the groundwater level depth in the six examined sites was close to the ground surface, ranging from a few meters to more than 25m below the ground surface, indicating that these sites were suitable for groundwater recharge.
- The geophysical results reveal the subsurface stratifications and their characteristics, thicknesses, depth to groundwater, geological structures and the favourable zones of ground water recharges.
- Based on the results of ERT, all six examined sites were found to be suitable for groundwater recharge, leading to the conclusion that the surrounding sites were also suitable for this purpose.

This study's findings lead to the following conclusions:

- The selection criteria used in this study are valid for identifying suitable groundwater recharge sites in similar environments.
- GIS is an effective platform for analyzing selection criteria and producing a final suitability map for groundwater recharge.
- Electrical Resistivity Tomography (ERT) is an effective tool for verifying the final suitability map for groundwater recharge.
- Well-data are crucial for validating the results of ERT data.
- The study area has a high potential for groundwater recharge.

It is recommendations based on the conclusions of this study:

The study area should be recognized as having a high potential for groundwater recharge, and initiatives should be taken to develop projects accordingly.

GIS and MCDA should be utilized for further research on groundwater recharge site selection in other parts of Jordan.

Whenever GIS techniques are employed to identify potential sites for groundwater recharge, geophysical investigations should be used with well-log data to validate the selected sites.
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