Assessing Water Resource Vulnerability to Climate Change in Al-karak, Jordan Based on GIS and Remote Sensing

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Abstract
Climate change and population growth exacerbate water scarcity in Jordan, highlighting the imperative for vulnerability assessments; however, the absence of a comprehensive framework with sufficient indicators hinders effective evaluation of water resource vulnerability. This research aims to determine spatial factors that can contribute to the vulnerability of water resources in the study area. Using the IPCC methodology, vulnerability is divided into three distinct components: exposure, sensitivity, and adaptive capacity. The study period spans from 1987 to 2022 (35 years). By employing remote sensing (RS), GIS techniques, and the analytical hierarchy process (AHP), fourteen indications were chosen based on their proximity to the measured component. The indicators were then normalized to produce a consistent scale ranging from 0 to 1. The study employs a geometric aggregation methodology to evaluate water resource vulnerability by integrating various indicators. The composite indicator (CI) is calculated by geometrically aggregating the vulnerability index (VI) of three components. This approach captures complex relationships and synergies among indicators, providing a comprehensive assessment of water resource vulnerability. The vulnerability map produced from the study illustrated vulnerability distribution throughout the area, highlighting notable high-vulnerability zones such as the AlQatraneh District, as well as portions of the northern and southern regions, including the Alghour District, characterized by arid conditions. Vulnerability values ranged from 0.44 to 0.5, with a notable concentration around 0.4, indicating substantial vulnerability. The study found a significant vulnerability in areas with a consistent decline in annual rainfall of 1.3 mm / year and a rise in annual variability of 2-3%. High-vulnerability areas experienced a significant increase in rainfall variability and temperature by 0.03°C /year, indicating continuous climate change. Piezometric data validated the vulnerability index map, with a Kappa index of 0.6552, attributed to factors such as declining precipitation, rising temperatures, and increased water demand due to population growth.

Keywords: Climate Change, Geographical Information System, Jordan, Vulnerability Assessments, Water Resource

1. Introduction

Climate change is anticipated to impact both the quantity and quality of water resources in Jordan. International assessments, including those conducted by the Intergovernmental Panel on Climate Change [1], have highlighted that region with already limited water resources, such as the Middle East and North Africa, are likely to experience exacerbated water scarcity. Past regional and local studies have observed a rise in mean temperatures, as well as an increase in the intensity and frequency of extreme temperatures, based on analyses of historical weather data. Climate change is anticipated to yield both overarching and localized impacts on the Earth's surface, including a reduction in freshwater reservoirs alongside heightened water demand [2]. The management of water resources has emerged as a paramount concern in this context. Jordan is heavily reliant on rainfall, and the prospects for water availability are not promising. The ensuing imbalance between availability and demand for water is likely to expand considerably as the climate changes. The Alkarak area is a semi-arid ecosystem that is known to be extremely vulnerable to climate change, with limited water resources primarily reliant on groundwater. However, climate change can alter the hydrological cycle's fundamental drivers.

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Climate change-induced longer droughts and rising temperatures have hastened the depletion of Jordan's groundwater resources. Over-extraction of groundwater for agricultural, industrial, and domestic reasons has caused a fall in water tables and increasing salinity levels [3]. In the context of water resources, vulnerability assessment typically involves evaluating the susceptibility of water systems to changes in precipitation patterns, temperature, evaporation rates, extreme weather events, sea-level rise, and other climate-related factors. This assessment may also consider the socio-economic factors that influence access to water, water demand, and the capacity to adapt to changing conditions [4]. There is a need to find a solution to reduce the impact of climate change and its impact on all life forms in the study area. To meet the growing demand on the agricultural, drinking, household, and industrial sectors, and to address various issues related to water resources management.

Several studies have conducted vulnerability assessments of water resources using GIS, as demonstrated by research conducted by [5][6][7][8] and [9]. However, despite these contributions, many studies have primarily focused on hydrological and climatic factors in vulnerability assessments, overlooking the significant role of socio-economic factors such as poverty rate and water demand. Integrating these socio-economic factors into vulnerability assessments can provide a more comprehensive understanding of vulnerability and aid in the development of effective adaptation strategies. On the other hand, vulnerability assessments conducted by Al-Karablieh and Salman [10] and [11], predominantly concentrated on surface water resources, neglecting the vulnerability of groundwater to climate change. This gap in research overlooks crucial aspects such as changes in recharge rates, water quality, and overall sustainability of groundwater resources.

The current study aims to address this gap by focusing specifically on spatial factors influencing the vulnerability of water resources within the designated study area. The specific objectives are: (1) to identify spatial elements that potentially impact the vulnerability of water resources in the study area, (2) Validate the Water Resources Vulnerability Index Map within the study area. This validation process is crucial for ensuring the effectiveness of the index map in accurately representing the vulnerability of water resources in the study area. By integrating spatial analysis techniques and pertinent data, this study seeks to provide valuable insights into understanding and addressing the challenges posed by water resource vulnerability, thus contributing to more informed decision-making and effective resource management strategies.

2. Materials and Methods

2.1 Study Area

The Al Karak Governorate, situated in the southern region of Jordan, spans approximately 3,495 square kilometers, boasting diverse geographical features (Figure 1). Its coordinates range between longitudes 35° 19′ 30″ and 36° 13′ 51″ and latitudes 30° 47′ 26″ and 31° 27′ 45″ [12]. Positioned 130 kilometers south of Amman, the capital, the governorate's cities vary in elevation from over 1000 meters above sea level in the South AlMazar Department to 330 meters below sea level at Ghor Al-Safi Department. Five morphoclimatic areas emerge due to distinct landforms across the region, including semi-arid and hyper-arid regions, mountainous areas, and low-lying regions approximately 400 meters below sea level.

The Mediterranean climate dominates the mountainous highlands, experiencing cold winters with rainfall between 200 to 400 mm and dry, hot summers. Conversely, the Jordan Valley regions exhibit a subtropical climate, characterized by even drier and hotter conditions compared to central and northern valleys. Limited agricultural land is available in the study area, primarily due to water scarcity and dam regulations. The Mediterranean climate prevails throughout the study area, featuring hot, dry summers and relatively mild winters, with minimal rainfall mainly occurring in winter. Positioned between the Mediterranean Sea and the Arabian Desert, the governorate experiences diverse climatic influences. The geographic landscape, comprising mountains, valleys, and limited water resources, significantly impacts various facets of life, including land use, economic activities, and societal dynamics. Understanding the geographical context is vital for conducting vulnerability assessments of water resources concerning climate change, utilizing GIS and remote sensing technologies. This understanding elucidates specific challenges and opportunities associated with water resource management and adaptation strategies within the Al Karak Governorate.

2.2 Data Description

Several criteria were chosen for the vulnerability assessment of water resources to climate change after a complete review of current literature and discussion with experts in the field. Establishing a model for evaluating water resources entails identifying relevant water factors.

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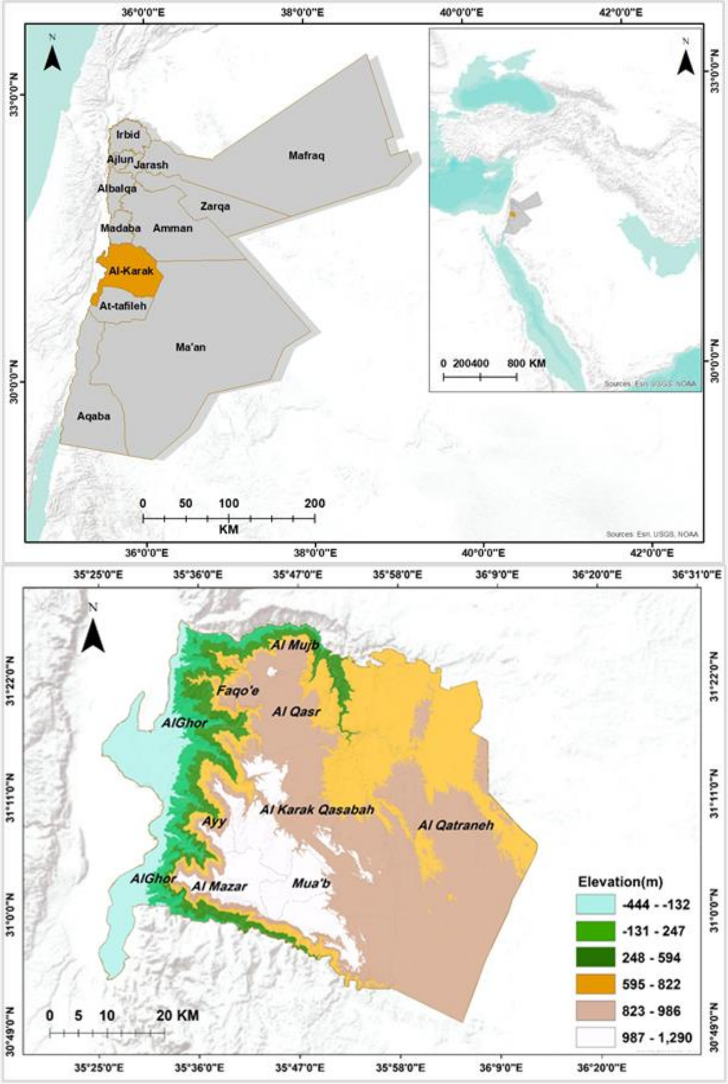

Figure 1: Al-karak, Jordan

In developing a model for assessing water resources, it is essential to identify parameters relevant to water-related aspects. However, there exists a lack of consensus regarding the specific criteria that should be employed for this analysis [13] and [14]. In addition, it is important to base the selection of criteria on the availability of data. constructing a vulnerability assessment of water resources map entails constructing a geographic database, integrating spatial data, applying the AHP approach, verifying the model with historical water resources data, and producing the final vulnerability index map, as illustrated in Figure 2. The following section contains detailed descriptions of these requirements.

Vulnerability assessment of water resources to climate change. Factors and their relevance differ between studies, resulting in inconsistency [15]. Researchers usually base their vulnerability assessments of water resource challenges on the research area's unique physical and ecological characteristics [16]. In the current study, a comprehensive literature review was conducted to identify and choose 14 vulnerability causative factors based on their relevance and significance, as indicated in previous research. Furthermore, the availability of geographic data is an important consideration when using factors or variables. Table 1 displays the indicators used and the data source for the vulnerability assessment of water resources.

2.3 Data Processing and Analysis

The indicators selected for the vulnerability assessment of water resources to climate change in the study area. Selection of these criteria was driven by their relevance to the assessment's objectives and the reliability of the available datasets in Figure 2.

Table 1: Indicators of vulnerability assessment of water resources

Component	Indicator	Code	Unit	Period	Data Source
Exposure	Precipitation(mm) (annual/daily)	E1	mm	1987-2022	Ministry of Water and Irrigation
	Temperature (annual/daily)	E2	°C	1987-2022	Ministry of Water and Irrigation
	Soil	E3	m	2022	Royal Jordanian Geographic center
	Landcover	E4	km^2	1987-2022	Satellite image from Landsat
Sensitivity	Groundwater recharge	S1	mm	2000-2020	Ministry of Water and Irrigation
	Groundwater quality	S2	mm	2000-2020	Ministry of Water and Irrigation
	Water demand	S3	mm	2000-2020	Ministry of Water and Irrigation
	Topography	S4	km^2	2022	Royal Jordanian Geographic Center
	Poverty rate	S5	person	1999 -2022	Department of Statistics
	Water consumption per capita	S6	m^3 /capita/year	1999-2022	Ministry of Water and Irrigation
	Population density	S7	people/km^2	2000-2022	Department of Statistics
Adaptive Capacity	Rainwater harvesting	A1	mm	2000-2020	Ministry of Water and Irrigation
	Wastewater treatment	A2	mm	2000-2020	Ministry of Water and Irrigation
	Greywater reuse	A3	mm	2000-2020	Ministry of Water and Irrigation

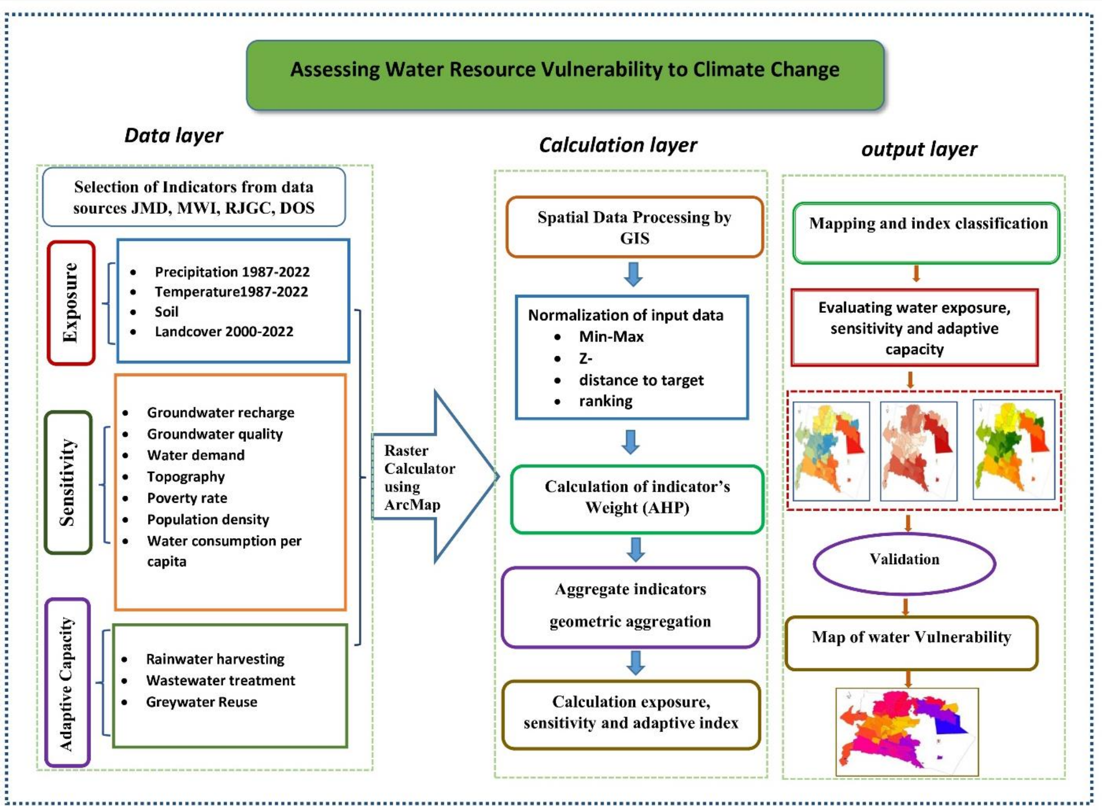

Figure 2: The framework of water vulnerability assessment to climate change

The water resource vulnerability assessment framework comprises three primary layers: the data layer, calculation layer, and output layer. Input data from various sources such as satellite data, statistical data, expert opinions and regional documents are collected for variables. These data are stored in a database system, with statistical data displayed in Microsoft Excel and spatial data processed by ArcGIS 10.8. The calculation layer involves five steps, including processing satellite images, normalizing input data, calculating data weights, and determining components and indicators following the vulnerability assessment method. The output layer presents assessment results through tables, maps, and graphs, integrating with Excel and ArcGIS 10.8. The module demonstrates exposure, sensitivity, and adaptive indices for provinces or ecological zones, as well as the water vulnerability index (VI) for specific time periods. Maps illustrate results, aiding policymakers and local authorities in identifying water vulnerability levels for regions and implementing effective management strategies. This approach was adopted to uphold result accuracy and safeguard the integrity of the study area. The ArcGIS platform was employed to reclassify and rank all selected criteria on a scale from 1 to 5, representing very low to very high vulnerability assessments of water resources. Cell sizes were established at a minimum of 30 m × 30 m to capture detailed ground-level information effectively. Figures 3, 4 and 5 depict all the layers created in this process. Specific details regarding each layer are elaborated upon in the subsequent subsections Figure 2. The framework of water vulnerability assessment to climate change.

2.3.1 Rainfall CV

Climate change influences precipitation patterns, impacting both the average and variability of precipitation [17]. Researchers employ the coefficient of variation (CV) to evaluate how climate change affects precipitation variability and its implications for water resources. The CV, calculated as the standard deviation divided by the mean, quantifies the variability of rainfall data. Using data from 11 rainfall monitoring stations spanning from 1987 to 2022, researchers generated annual rainfall CV distribution maps via inverse distance weighted (IDW) interpolation in ArcGIS 10.8. IDW, a robust interpolation technique, predicts values at unknown locations based on known ones. The study reveals significant rainfall variability in the western area (CV > 40.0), with moderate variability in the middle (CV around 30.0). Overall, the basin experiences substantial relative rainfall variability, highlighting the impact of climate change on precipitation pattern in Figure 3(a).

2.3.2 Temperature

Temperature is an important element in hydrological processes and water supply. Integrating temperature indicators into vulnerability assessments allows researchers to better grasp the complex interactions between temperature-driven changes and other variables, resulting in a more complete knowledge of water resource vulnerability [8] and [15]. Temperature data for four meteorological stations: using data from 1987 to 2022. The study area annual mean temperature was divided into five classes. (18.5-19), (5 19.6-21), (0 21.1-22.4), (22.5-23.6) and (23.7-25.5). The distribution of annual temperatures was generated utilizing the inverse distance weighted (IDW) interpolation technique within the ArcGIS 10.8 software platform as shown in Figure 3(b).

2.3.3 Soil type

Soil is the top layer of the earth's crust that develops slowly due to the weathering process [18]. Depending on the soil texture. Alkarak soil texture can be separated into five soil groups, as indicated in Figure 3(c) illustrates the spatial distribution of soil texture classes at Alkarak. using ArcMap to convert the shapefile representing Soil Type into a raster format, use the Feature to Raster tool in ArcMap. The spatial distribution of soil texture classes helps identify areas that are more susceptible to erosion, as different soil textures have varying levels of stability.

2.3.4 Landcover

The use of landcover and indicators in the study of Vulnerability Assessment of Water Resources to Climate Change, it helps in identifying vulnerable areas, understanding the impacts of land use changes on water resources [18]. The landcover maps were generated using Landsat 5 and Landsat 8 imagery acquired from the USGS Earth Explorer. The selection of the years, specifically 1987 and 2022, was based on the availability of cloud-free data for the study areas. The satellite imagery bands were processed by combining, re-projecting, and clipping using layer stacking techniques. The supervised classification method was then applied to extract land cover features from the processed imagery. Change detection maps were created and analyzed using ArcGIS software, by using the Image Analysis and Spatial Analyst toolboxes utilizing the Image Analysis and Spatial Analyst toolboxes. This approach provided valuable insights into the changes and trends in landcover over the study period as shown in Figure 3(d).

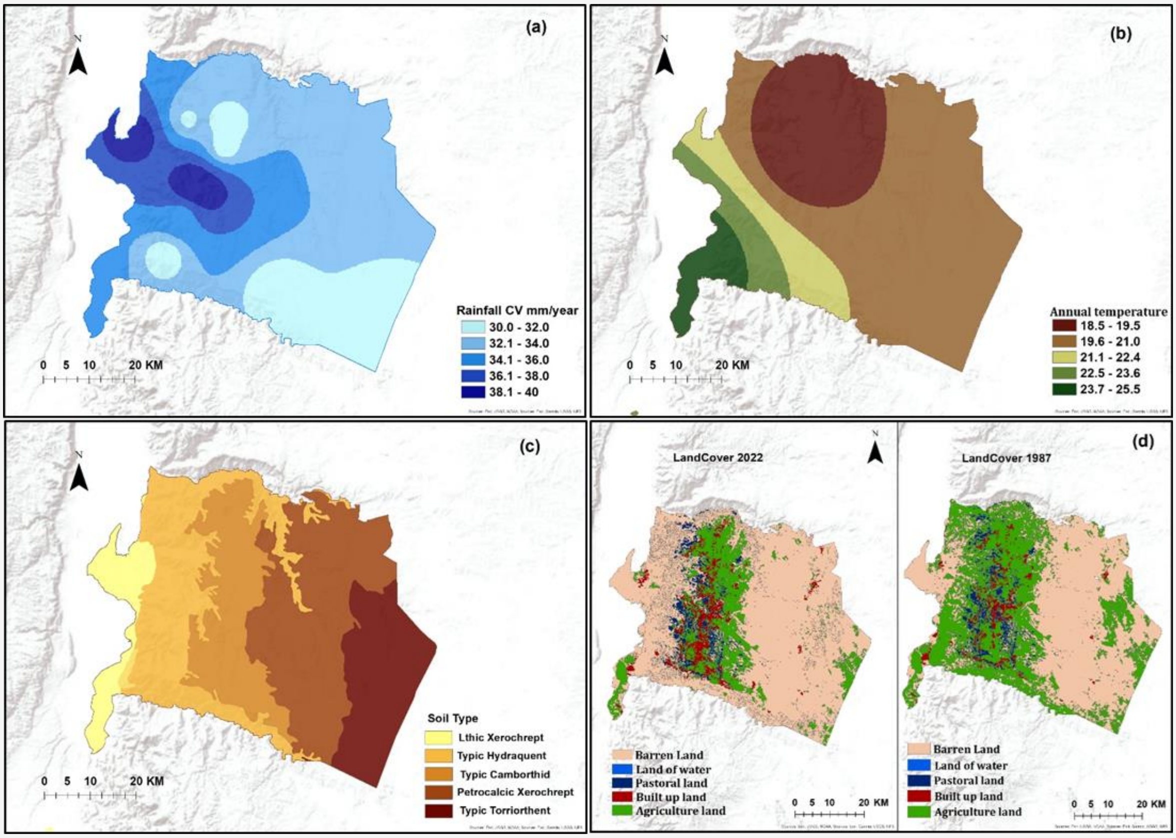

Figure 3: Exposure indicators:
(a) Coefficient variation rainfall from 1987 to 2022 (b) Annual temperature from 1987–2022.
(c) Distribution of soil texture (d) Change in the types of land cover between 1987 and 2022

2.3.5 Groundwater recharge

Groundwater, a crucial natural resource globally, undergoes recharge, a pivotal aspect of water resource management, influenced by precipitation, terrain, and soil cover [19]. Monitoring groundwater levels through observation wells and employing the J2000 water balance model, based on a water budget approach, allows for the estimation of recharge rates. Recharge rates(D) (mm/year) are calculated using Equation 1:

$$D = P - ET - \Delta S - Roff \qquad \text{Equation 1}$$

Where *P* is precipitation, *ET* is evapotranspiration, *ΔS* is change in soil water storage, and *Roff* is runoff. Figure 4(a) illustrates groundwater recharge volumes from 1987 to 2022 in the study area, averaging 39.9 million cubic meters per year (MCM/ year). The area is classified into five categories, exhibiting recharge rates ranging from less than 20 MCM to 49 MCM. Utilizing inverse distance weighted (IDW) interpolation within ArcGIS, groundwater recharge data was generated to provide spatial insights into recharge dynamics across the study area.

2.3.6 Groundwater quality

Groundwater quantity and quality vary due to natural and human-induced factors like climate, hydrogeology, management practices, and pollution. Increased water demand often leads to groundwater depletion [20]. Evaluating groundwater quality involves tools like the Water Quality Index (WQI), which combines multiple parameters into a single value. Parameters like Langelier Saturation Index (LSI), Ryznar Stability Index (RSI), Aggressiveness Index (AI), and Permeability Index (PI) contribute to the WQI score. WQI categorizes water quality into classes based on thresholds: Excellent (WQI < 50), Good (50 ≤ WQI ≤ 100), Poor (100.1 ≤ WQI ≤ 200), Very Poor (200.1 ≤ WQI ≤ 300), and Unsuitable for Drinking (WQI > 300). Creating groundwater quality maps involves using the IDW interpolation technique within ArcGIS software as shown in Figure 4(b).

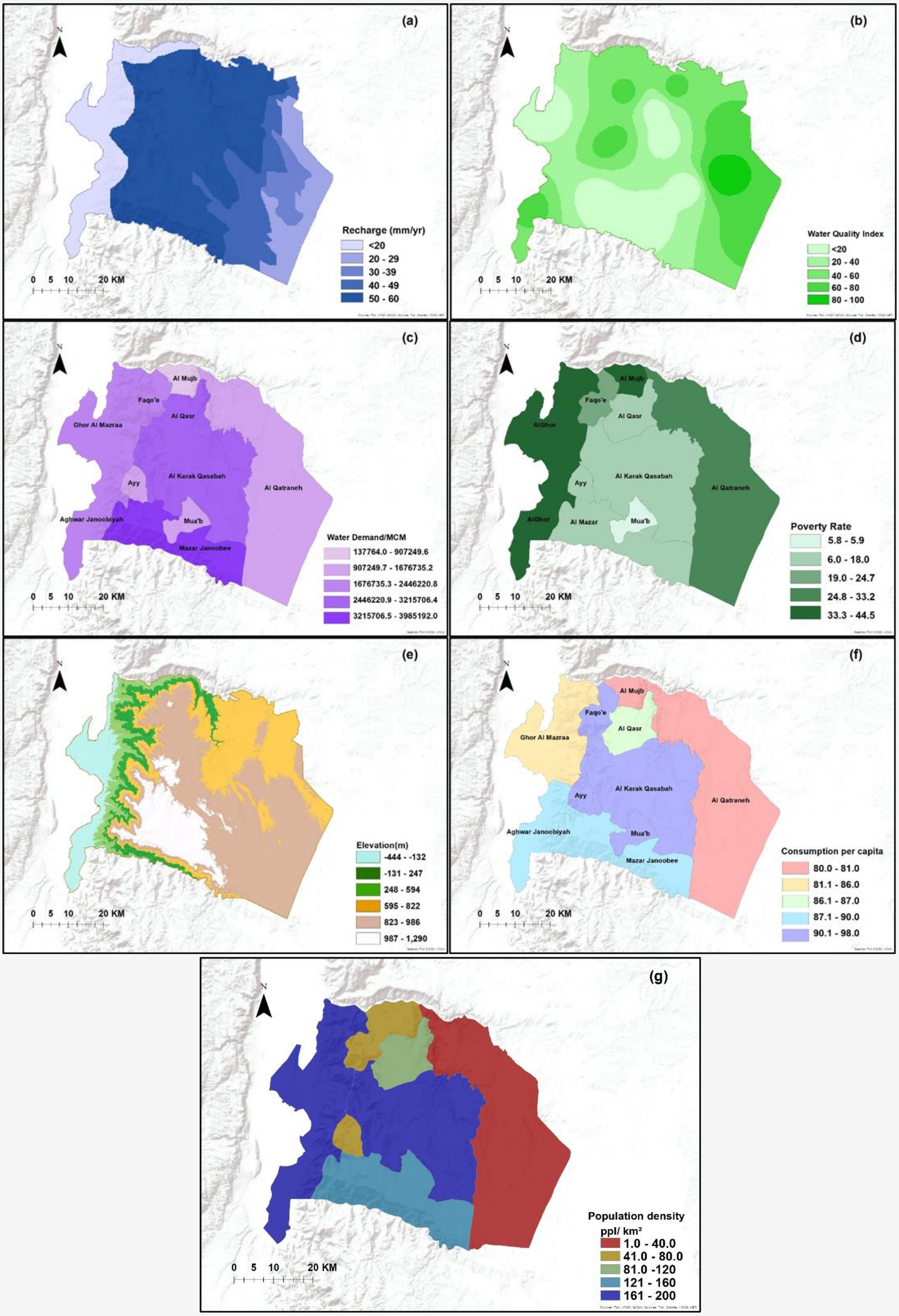

Figure 4: Sensitivity indicators:
(a) Groundwater recharge (b) Groundwater quality (c) Demand water (d) Poverty rate (e) Topography (f) Water consumption per capital (g) Population density

2.3.7 Water demand

The Water Demand Indicator, which integrates demographic, socioeconomic, bulk demand, and climatic aspects to explain water demand patterns, is discussed by [21]. The rise in water demand, juxtaposed with diminishing availability, underscores challenges in water management, leading to scarcity and sustainability concerns. Municipal water supply in Jordan has steadily increased from 9,244,742 to 12,633,789 million cubic meters (MCM) between 2011 and 2023, with per capita daily consumption rising from 144 to 150 liters. Agriculture is the primary water consumer, followed by municipal and industrial sectors. The study area was classified into five consumption classes, ranging from 5.5-6 to 7.6-8 MCM per year, and water demand data were illustrated within district boundaries (Figure 4(c)).

2.3.8 Topography (m)

Topography significantly influences local climate patterns, particularly precipitation [22] and groundwater recharge, with flat or gently sloping regions favoring increased infiltration [23]. Using a 10m resolution DEM, this study characterizes the varied topography of Karak governorate, ranging from -400 meters below sea level along the Dead Sea coasts to 1321 meters above surface level in AlMazar's highlands. The study divides the region into five elevation classes, illustrating the topographic diversity in Figure 4(d).

2.3.9 Poverty rate

The poverty rate, indicating the proportion of individuals living below the poverty line, serves as a crucial metric for assessing socio-economic well-being and inequality within a population [24]. Data on poverty rates for the study area were sourced from the Department of Statistics in 2023. The poverty rate ranges in Alkarak from 18.1% to 5.9%, as depicted in Figure 4(e).

2.3.10 Water consumption per capita

Water consumption per capita, the average water usage per individual over a specified period and geographical area, is calculated by dividing total water consumption by the population [25]. Jordan, ranking second globally with minimal water resources, faces severe scarcity, with yearly renewable water resources below 100m³ per person [26]. The Ministry of Water and Irrigation underscores water's critical significance as demand exceeds supply, with each individual allocated just over 90 cubic meters annually, projected to decrease further to as low as 60 cubic meters by 2040, as illustrated in Figure 4(f).

2.3.11 Population density

Population density significantly influences water resources and management, impacting both supply and quality [27]. It correlates with increased water consumption, stress on supply, and heightened vulnerability to climate change [28] and [5]. This study reveals district population densities ranging from 10.3 to 192.9 people per km², with Al-Mazar district in southern Alkarak exhibiting the highest density, as depicted in Figure 4(g).

2.3.12 Treated wastewater

The presence of three wastewater treatment plants (WWTPs) in urban centers, treating over 3392 MCM, of wastewater annually, as per [29], reflects Jordan's commitment to sustainable water management [30]. Strategic WWTP placement enables efficient wastewater reuse for irrigation, fostering agricultural development while conserving freshwater resources. The creation of a Treated Wastewater distribution map using IDW interpolation in ArcGIS 10.8 reveals five classes ranging from 712 MCM to 1369 MCM, as depicted in Figure 5(a).

2.3.13 Rainwater harvesting

Rainwater harvesting, increasingly adopted in water-scarce regions like semi-arid areas, enhances water accessibility and meets household and agricultural needs effectively [31]. The Jordan Valley Authority has implemented numerous rainwaters harvesting projects, comprising 425 sites with a total designed storage capacity of 123.2 million cubic meters, distributed across different governorates [5], as depicted in Figure 5(b). Storage water in the study area ranged from 0.13 MCM to 10.47 MCM by the end of 2022.

2.3.14 Greywater reuse

Greywater, a significant potential water source, contributes to reducing freshwater consumption and enhancing sustainability [32], particularly crucial in regions facing altered precipitation patterns and increased drought occurrences [33]. A project implemented in Karak from February 2004 to October 2007 involved installing 110 greywater systems, meeting Jordanian and WHO standards for treated wastewater usage [34]. These initiatives, divided into 'Phase I' and 'Phase II,' were linked by common aims [34] and [35], with all treated greywater utilized for irrigation (200-300 L/day). Data obtained from MWI was integrated into ArcGIS within district boundaries, as depicted in Figure 5(c).

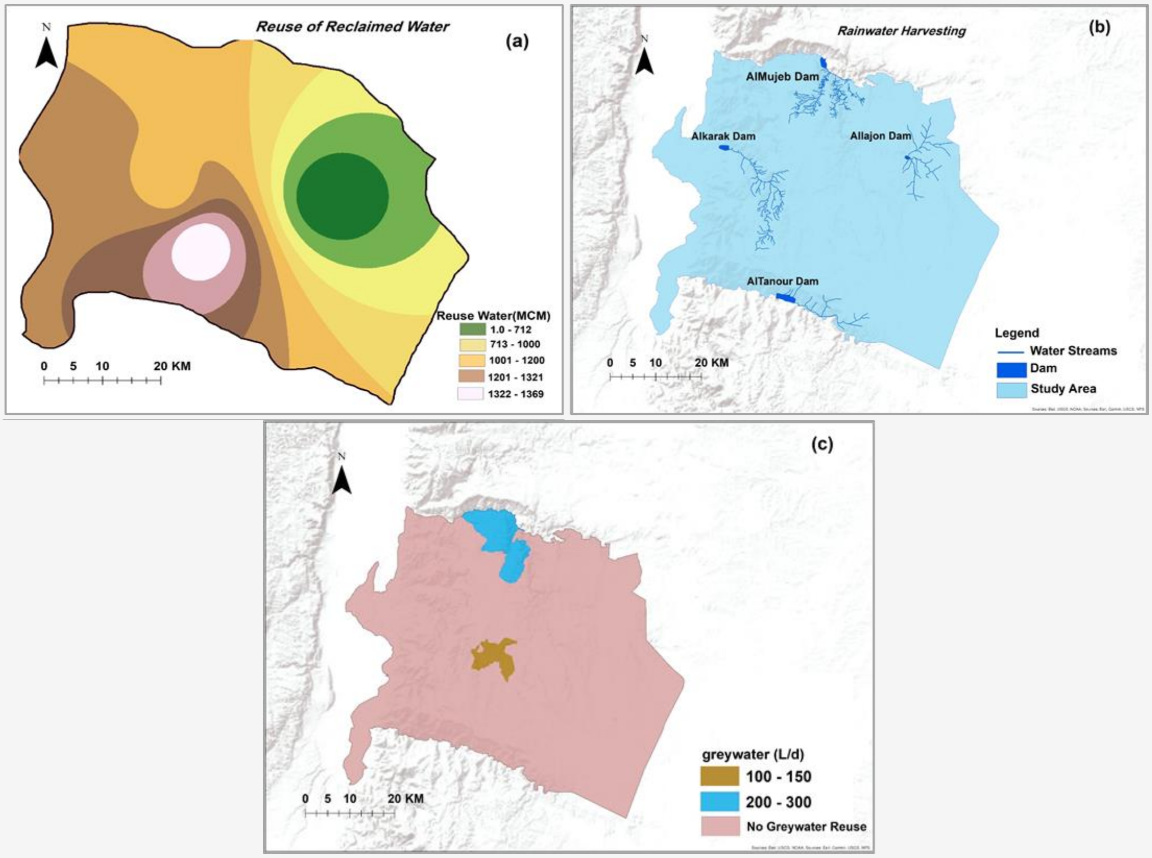

Figure 5: Adaptive capacity indicators: (a)Treated wastewater (b) Rainwater harvesting(c) Greywater reuse

2.4 Indicator Weighting Using AHP

The Analytical Hierarchy Process (AHP), devised by [36], is a widely utilized multi criteria decision-making method for prioritizing indicators across diverse measurements, accommodating minor contradictions in assessments [37]. Commonly applied in various environmental studies, including vulnerability assessment of water resources, AHP facilitates breaking down complex problems into smaller components, utilizing expert judgment to determine relative priorities within a hierarchy. In this study, 15 local specialists, including water resource managers, hydrologists, climate change scientists, and environmental engineers, were consulted to gather data and insights, aiding in pairwise comparisons for generating a (14x14) matrix. This matrix assigns relative weights to criteria, enabling informed decision-making. Factors are ranked on a scale from 1 to 9, with 9 indicating the highest importance and 1 indicating the lowest. The weight of each factor is determined, and the random consistency ratio (CR) of the decision matrix is assessed using Equations (2) and (3). The CR value less than 0.1 signifies an efficient judgment matrix. In such cases, the maximum eigenvector is normalized to obtain the final weight.

$$CR = \frac{CI}{RI}$$

Equation 2

Where:

RI: random consistency index

CI: consistency index

$$CI = \frac{\lambda_{\max} - n}{n-1}$$

Equation 3

To proceed with the analysis, λ_{max} represents the principal eigenvector computed using the eigenvector technique, and n signifies the number of criteria.

2.5 Vulnerability Assessment

Several recent research [8][13] and [38], have taken a holistic approach to water resources and suggested approaches for calculating a vulnerability index (VI). The calculation of the Vulnerability Index, which combines the Exposure Index, Sensitivity Index, and Adaptive Capacity, is a critical step in assessing a system's or region's overall vulnerability to climate-induced threats. Each component of this composite index provides unique insights: Exposure identifies potential threats, Sensitivity demonstrates the system's responsiveness, and Adaptive Capacity evaluates its ability to cope and adjust. The most common techniques in water resource risk assessment, especially in a holistic approach, are factor selection, factor weighting, and data. The most crucial step involves normalizing input datasets using equation 4 that incorporates the UNDP's Human Development Index (HDI) [40] and [40]. Every factor minimum value becomes 0, its maximum value becomes 1, and every other value becomes a decimal between 0 and 1.

$$X_{ijNorm} = \frac{X_{ij} - X_{ijMIN}}{X_{ijMAX} - X_{ijMIN}}$$

Equation 4

When, X_{ij} represents the normalized score of the *j* indicator for the *i*th area.

The guidelines for aggregating composite indices are extensively outlined in the Handbook on the Construction of Composite Indices [41]. Geometric aggregation, involving the multiplication of normalized weighted indicators, is selected to address concerns regarding interaction and compensability [42], proving suitable for amalgamating non-comparable data on a ratio scale, provided indicators remain strictly positive [43]. The geometric mean, computed through a specific formula, considers variations in achievement across dimensions, with subpar performance in any dimension or indicator directly influencing the composite indicator value. However, this technique exhibits partial compensability, as it rewards composite indicators with higher scores on individual indicators, as discussed by [44]. Aggregation of all relative vulnerabilities of each factor is achieved using the "ArcGIS 10.8, Map Algebra, Raster Calculator" tool.

The subsequent formulas delineate the method for computing the composite indicator ($CI_{Exposure}$) for various components within the framework. The composite indicator is defined in Equation 5.

$$CI_{Exposure} = (EX_1)^{w1} \cdot (EX_2)^{w2} \cdot (EX_3)^{w3} \cdot \ldots \cdot (EX_n)^{wn}$$

Equation 5

Where *EXi* represents the normalized and assessed exposure indicators, *w* signifies the weighing value w_i, and *n* denotes the number of indicators. Sensitivity component is defined in Equation 6.

$$CI_{sensitivity} = (SE_1)^{w1} \cdot (SE_2)^{w2} \cdot (SE_3)^{w3} \cdot \ldots \cdot (SE_n)^{wn}$$

Equation 6

Where SE_i signifies the normalized and evaluated sensitivity component, *w* denotes the weighing value *wi*, and n represents the number of indicators.

Adaptive capacity components is defined in Equation 7.

$$CI_{ACi} = (AC_1)^{w1} \cdot (AC_2)^{w2} \cdot (AC_3)^{w3} \cdot \ldots \cdot (AC_n)^{wn}$$

Equation 7

As a result, consolidating the last two factors, Potential Impact and Adaptive Capacity, is imperative in deriving a comprehensive vulnerability assessment. The appropriate approach for aggregating these weighted components is expressed in Equation 8.

$$VI = (PI_x)^{wPI} \cdot (AC_x)^{wAC}$$

Equation 8

Where PI_x denotes Potential Impact and AC_x signifies Adaptive Capacity. The corresponding weights are represented by *wPI* and *wAC*, respectively.

2.6 Validation of Vulnerability Map

Validating a model that incorporates various dimensions such as socio-economic, hydrological, potential sources of pollution, and eco-environmental factors is challenging. Some researchers, like [45][46][47][48] and [49], who conducted integrated assessments of water resource vulnerability, did not include validation modules for their models. However, in [50] authors employed a simulation-based integrated water resources vulnerability assessment model and validated their findings using observational data from four key factors. In contrast, researchers like [51] and [52] used the DRASTIC method to evaluate water resource vulnerability to pollution, assuming that observing one or more physical and chemical water parameters would validate the final vulnerability map.

To validate the final water resources vulnerability map in the study area, data from 1987 to 2022 from 21 stations were utilized [53]. Piezometric data in vulnerable areas was analyzed for validation purposes. Additionally, water resources quality data from 40 monitoring sites, including 9 surface water stations and 31 groundwater stations spanning 30 years, were examined. This data was categorized into five classifications: extremely poor, poor, medium, good, and excellent. A confusion matrix was created

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to compare these classifications with the categories of the overall water resources vulnerability map. Finally, the Kappa index, introduced by Cohen in 1960, was calculated to assess the agreement between the water quality classifications and the vulnerability map categories, providing a quantitative measure of validation.

3. Results and Discussion

3.1 Weights of Indicators using AHP

The weight of each index indicator/factor on the vulnerability of the water resource system illustrates how these elements influence the evaluation results. The Analytic Hierarchy Process computes each index weight (Wi) (AHP). According to methodology, the weight indicators were organized in a three-level hierarchy. The first phase is gathering the experts' judgments, and the pair-wise comparison matrix and the final factor weight of each criterion were obtained from the AHP approach as shown in Table 2 and Table 3. After calculating the CI value (0.077) and the supplied value RI (1.57) from Table Values for random index, the consistency ratio CR is 0.047. The calculated value is less than the maximum allowable value (0.1), based on that, the value is acceptable, and the Analytical Hierarchy Process (AHP) indicates that the consistency of all factors employed in this analysis is acceptable. The weights assigned to each indicator in the vulnerability assessment are illustrated in Table 4.

3.2 Reclassification of Indicators

The data layers were converted to raster format for consistent evaluation and standardization, followed by reclassification into five comparable classes. This study utilized a reclassification table considering several factors affecting water resource vulnerability, summarized in Table 5. Each thematic layer's classes were rated based on their relative importance: very high (5), high (4), moderate (3), low (2), and extremely low (1), integrating expert knowledge and analysis for descriptive assessment**.**

Table 2: Pairwise comparison matrix

Criteria	A	B	C	D	E	F	G	H	I	J	K	L	M	N
A	1.00	2.00	2.00	2.00	5.00	3.00	2.00	2.00	3.00	5.00	9.00	5.00	4.00	3.00
B	0.50	1.00	2.00	2.00	6.00	3.00	2.00	2.00	3.00	2.00	9.00	5.00	4.00	3.00
C	0.50	0.50	1.00	0.50	5.00	2.00	1.00	0.50	2.00	5.00	7.00	4.00	3.00	2.00
D	0.50	0.50	2.00	1.00	6.00	3.00	2.00	2.00	3.00	6.00	9.00	5.00	4.00	3.00
E	0.20	0.17	0.20	0.17	1.00	0.25	0.20	0.20	0.25	0.50	3.00	0.50	0.33	0.25
F	0.33	0.33	0.50	0.33	4.00	1.00	0.50	0.50	2.00	4.00	6.00	3.00	2.00	2.00
G	0.50	0.50	1.00	0.50	5.00	2.00	1.00	0.50	2.00	5.00	7.00	4.00	3.00	2.00
H	0.50	0.50	2.00	0.50	5.00	2.00	2.00	1.00	2.00	5.00	8.00	4.00	3.00	3.00
I	0.33	0.33	0.50	0.33	4.00	0.50	0.50	0.50	1.00	4.00	2.00	3.00	2.00	2.00
J	0.20	0.50	0.20	0.17	2.00	0.25	0.20	0.20	0.25	1.00	3.00	0.50	0.33	0.33
K	0.11	0.11	0.14	0.11	0.33	0.17	0.14	0.13	0.50	0.33	1.00	0.25	0.20	0.17
L	0.20	0.20	0.25	0.20	2.00	0.33	0.25	0.25	0.33	2.00	4.00	1.00	0.50	0.33
M	0.25	0.25	0.33	0.25	3.00	0.50	0.33	0.33	0.50	3.00	5.00	2.00	1.00	0.50
N	0.33	0.33	0.50	0.33	4.00	0.50	0.50	0.33	0.50	3.00	6.00	3.00	2.00	1.00
SUM	5.46	7.23	12.63	8.39	52.33	18.50	12.63	10.44	20.33	45.83	79.00	40.25	29.37	22.58

Table 3: Normalized pairwise comparison matrix

Criteria	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Weights
A	0.18	0.28	0.16	0.23	0.10	0.16	0.16	0.19	0.15	0.11	0.11	0.12	0.14	0.133	0.159
B	0.09	0.14	0.16	0.23	0.11	0.16	0.16	0.19	0.15	0.04	0.11	0.12	0.14	0.133	0.139
C	0.09	0.07	0.08	0.06	0.10	0.11	0.08	0.05	0.10	0.11	0.09	0.10	0.10	0.089	0.087
D	0.09	0.07	0.16	0.11	0.11	0.16	0.16	0.19	0.15	0.13	0.11	0.12	0.14	0.133	0.132
E	0.04	0.02	0.02	0.02	0.02	0.01	0.02	0.02	0.01	0.01	0.04	0.01	0.01	0.011	0.019
F	0.06	0.05	0.04	0.04	0.08	0.05	0.04	0.05	0.10	0.09	0.08	0.07	0.07	0.089	0.064
G	0.09	0.07	0.08	0.06	0.10	0.11	0.08	0.05	0.10	0.11	0.09	0.10	0.10	0.089	0.087
H	0.09	0.07	0.16	0.06	0.10	0.11	0.16	0.10	0.10	0.11	0.10	0.10	0.10	0.133	0.106
I	0.06	0.05	0.04	0.04	0.08	0.03	0.04	0.05	0.05	0.09	0.03	0.07	0.07	0.089	0.055
J	0.04	0.07	0.02	0.02	0.04	0.01	0.02	0.02	0.01	0.02	0.04	0.01	0.01	0.015	0.024
K	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.007	0.012
L	0.04	0.03	0.02	0.02	0.04	0.02	0.02	0.02	0.02	0.04	0.05	0.02	0.02	0.015	0.027
M	0.05	0.03	0.03	0.03	0.06	0.03	0.03	0.03	0.02	0.07	0.06	0.05	0.03	0.022	0.038
N	0.06	0.05	0.04	0.04	0.08	0.03	0.04	0.03	0.02	0.07	0.08	0.07	0.07	0.044	0.051
Column sum	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.000	1.000

Table 4: Results of the weight calculation

Criteria	Indicator Name	Weight
A	Rainfall CV	0.158
B	Temperature	0.139
C	Landcover	0.090
D	Population density	0.132
E	Soil	0.018
F	Groundwater recharge	0.064
G	Groundwater quality	0.087
H	Water demand	0.106
I	Topography	0.055
J	Poverty rate	0.024
K	Water consumption per capita	0.012
L	Rainwater harvesting	0.027
M	Greywater reuse	0.038
N	Wastewater treatment	0.051

Table 5: Reclassification of the criteria and their rating

Criteria	**Rating**				
	1	**2**	**3**	**4**	**5**
Rainfall CV (mm/day)	30.0-32.0	32.1-34.0	34.1-36.0	36.1-38.0	36.1-38.0
Temperature	18.5-19.5	19.6-21.0	21.1-22.4	22.5-23.6	23.7-25.5
Soil type	Camborthid	Chromoxere	Xerochrept	Calciorthid	Hydraquent
Landcover	Barren land	Pastoral land	Land of water	Agriculture land	Built up land
Population density (per km^2)	1.0-40.0	41.0-80.0	81.0-120	121-160	161-200
Groundwater recharge	<20	20–29	30–39	40–49	50–60
Groundwater quality	> 300	200 – 30	100 – 200	50 – 100	<50
Water demand	7.6-8	7.1-7.5	6.6-7	6.1-6.5	5.5-6
Topography (m) Poverty rate	938-1295	681-937	331-680	-86- -330	-400--85
Poverty rate	10>	10 -20	21-30	31-40	41-50
Water consumption per capita	80-90	91-100	101 -120	121 - 130	131-14
Treated wastewater	<1	1 -712	713-1321	1322-1369	-
Rainwater harvesting	0.100- 2.01	2.100-4.01	4.10-6.01	6.10-8.01	8.10-11
Greywater reuse	100-200	200 - 300	-	-	-

3.3 Exposure Index

Exposure indicators are measurements or variables used to estimate a system's or population's exposure to climate change impacts [1]. The exposure map in Figure 6 was developed to show which parts were highly exposed to climate hazards.

According to the exposure map Al-Qatraneh district, Alghour, almujeb district in north were highly exposed. The highest part exposed was AlQatraneh with 65%. Regions with high decline and variability in rainfall mainly contributed to high exposure.

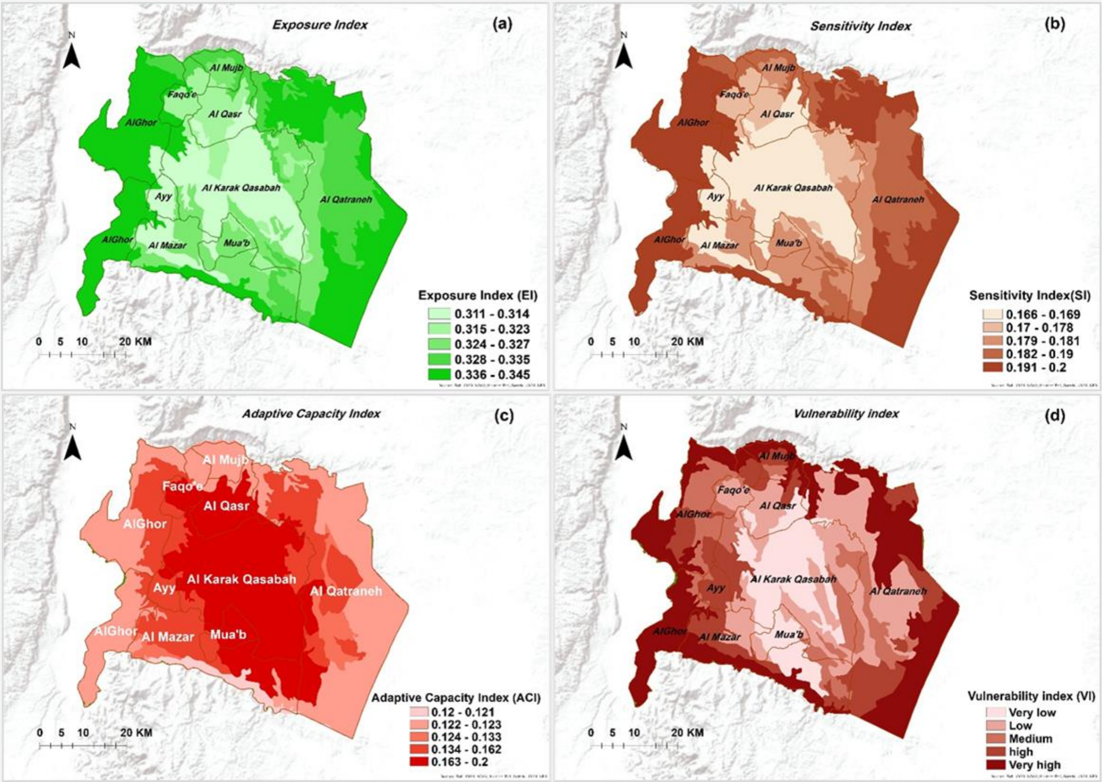

Figure 6: (a) Exposure index (b) Sensitivity index (c) Adaptive capacity index (d) Vulnerability index

High temperature trends showed an increase in temperature that results in increased evaporation rates leading to drying up, pasture and crops causing increased drought situations decrease water resources. Overall, the analysis conducted within the exposure component gives us a glimpse of the climate dynamics that the community is exposed to over time, and, thus, bringing the sensitivity and lack of adaptive capacity allows us to analyze the vulnerability of the community within the context of climate change.

3.4 Sensitivity Index

The most sensitive areas were identified in Alkarak. All indicators appeared to influence sensitivity in various locations to varying degrees. AlQatraneh exhibited high sensitivity, reaching 70% as depicted in Figure 6. This may be attributed to its elevated water demand, with water consumption per capita falling below 90 m^3 per person, and a relatively high poverty level in the AlQatraneh and Alghour district. Groundwater recharge analysis indicated a decrease in both level and quality.

3.5 Adaptive Capacity

In Al Karak, sites with a high adaptive capacity component were identified. Various markers appear to have different effects on adaptation across several sites. Water treatment, rainwater collecting, and graywater treatment are all important practices for adjusting to changing climates. Rainwater collection aids in groundwater recharging and serves as an important supply of surface water. Wastewater treatment also reduces agricultural water consumption and pollution. The use of gray water in agricultural activities yields similar benefits (Figure 6).

3.6 Vulnerability Index

The study involves conducting vulnerability assessments and proposing methodologies to compute a Vulnerability Index (VI). The VI integrates three key components: The Exposure Index, Sensitivity Index, and Adaptive Capacity. These elements collectively assess the susceptibility of a system or region to climate-induced risks. Each component provides unique insights: Exposure identifies potential hazards, Sensitivity reveals the system's responsiveness, and Adaptive Capacity evaluates its ability to cope and adapt. Typical procedures in water resource vulnerability assessment, especially within a holistic framework, include selecting relevant factors, assigning weights to these factors, standardizing data, and aggregating factors to form a composite vulnerability index.

Table 6: Results of water resources vulnerability assessment for the district zones

District Name	Vulnerability Index	Vulnerability Level
AlQasabeh	0.422	Very low
AlQatraneh	0.542	Very high
Almazar	0.456	Medium
Alqaser	0.445	Medium
AlGhour	0.515	High
Ayy	0.489	High
Faqo'e	0.446	Medium
Al Mujb	0.545	Very high
Mua'b	0.424	Low

Figure 6, depicts the spatial distribution of vulnerability within the study area, highlighting notable high-exposure regions such as the Alghour, AlQatraneh, and part at the northern and southern boundaries. Vulnerability values ranged from 0.44 to 0.5, with a distinct concentration around 0.4, indicating a significant level of vulnerability. Indicators contributing to heightened vulnerability in these regions include decreasing precipitation, rising temperatures, increased water demand due to population growth, socio-economic challenges indicated by the poverty index, and unique population densities. Additionally, the limited implementation of effective adaptation measures within the region further exacerbates vulnerability levels.

Table 6 displays the vulnerability index and corresponding vulnerability levels for various districts. Districts such as AlQatraneh and Al Mujb exhibit very high vulnerability levels with vulnerability indices of 0.54213 and 0.54512 respectively. AlGhour and Ayy also demonstrate high vulnerability levels with indices of 0.5154 and 0.4895, respectively. Districts like Almazar and Faqo'e show medium vulnerability levels, while AlQasabeh and Mua'b display lower vulnerability levels categorized as extremely low and low, respectively. The research findings confirm the objective of exploring the intricate relationship between spatial variables and water resource vulnerability in the study area. Analysis reveals that factors such as precipitation, temperature, soil, land cover, population density, water demand, groundwater recharge, topography, and groundwater quality significantly contribute to observed vulnerabilities in water resources. These spatial insights not only enhance comprehension of environmental dynamics but also offer crucial data for formulating targeted mitigation and management strategies. This research emphasizes the importance of considering spatial factors when evaluating water resource vulnerability, emphasizing their influence on current water quality and availability. The implications extend beyond the study, informing future research, resource management practices, and policy development in similar geographical contexts.

In semi-arid regions, the impacts of climate change, population growth, and human activities exacerbate water resource vulnerabilities. Erratic precipitation, prolonged droughts, and increased evaporation rates intensify stress on water sources. Therefore, developing a vulnerability index is crucial for identifying and prioritizing high-risk areas, facilitating tailored and adaptive water resource management strategies. A vulnerability index serves as a valuable decision-support tool for policymakers, water resource managers, and stakeholders involved in sustainable water management. By quantifying water resource vulnerability, decision-makers can efficiently allocate resources, implement mitigation measures, and plan for resilience, thereby enhancing overall sustainability and resilience of the water supply system.

3.7 Validation of Vulnerability Map

This study focusing on the vulnerability of water resources to climate change, particularly related to groundwater quantity and quality in the study area, the final water resource vulnerability index map was validated using various data sources. Water resources quality data spanning from 1987 to 2023 from 21 stations [54], were utilized for validation purposes. Additionally, piezometric data from vulnerable locations were analyzed.

Specifically, the validation process involved examining piezometric data from different areas. In Alkarak AlQasabeh and Almazar district, a significant decline in piezometric levels was observed from 1m in the 1970s to 5m in 2020. Similarly, in Almujeb, there was a notable reduction in piezometric levels between 2006 and 2018, with the deepest wells experiencing a decrease from 2.5 m to 6 m. AlQatraneh also exhibited a definite drop in water level across several wells from 1996 to 2021, with the most substantial decrease recorded from 2 m to 10 m deep.

Furthermore, AlQatraneh experienced multiple dry periods in recent years, including one in August 2018. In Alghour, a considerable reduction in piezometric level was noted from 1m in the 1980s to 11m in 2015. Similar to AlQatraneh, AlGhour also faced several dry spells, with the most recent occurring between August 2013 and 2019**.**

Long-term water quality data is critical for understanding water quality dynamics and trends across time. This study conducted a comprehensive analysis of 20 years of data obtained from 50 water quality monitoring stations, including 9 surface water stations and 41 groundwater stations. The data were divided into five categories, ranging from very bad to good quality. Furthermore, a confusion matrix was created to investigate the association between these water quality classes, and the vulnerability classes represented on the total water resources vulnerability map, yielding a Kappa index of 0.6552. According to Cohen's classification scheme, this index indicates a significant level of agreement between the water quality classifications and the vulnerability map classes.

4. Conclusions

Assessing water vulnerability accurately is crucial for understanding the impacts of climate change and human activities on water resources, particularly for informing future water management strategies. While existing vulnerability assessment methods face challenges due to data impracticality and availability, this study introduces a novel framework integrating satellite imagery and GIS-based models. This approach proves advantageous for its adaptability to the complex nature of vulnerability assessment.

The research presents the first comprehensive vulnerability assessment of water resources in Alkarak, focusing on key impact aspects such as precipitation, temperature, population density, and topography. Results indicate high vulnerability in AlGhour and AlQatraneh districts, with land use/land cover emerging as the dominant parameter contributing 27% to the vulnerability index. The study identifies indicators like precipitation, temperature, population density, water demand, and groundwater quality as significant contributors to water quantity vulnerability.

The expanding population in Alkarak, coupled with increasing surface infrastructures, exacerbates susceptibility to water quantity vulnerability. Future research directions should explore scenarios such as population growth, water availability, and climate change to refine the framework's resolution in identifying vulnerable hotspots. Challenges within the study area related to climate change, increasing human pressure, unsustainable land use practices, and soil are addressed through a GIS modeling approach. The study underscores the role of vulnerability as a barrier to sustainable development, emphasizing the need for mitigation strategies. Lastly, the model's applicability in other semi-arid environments is highlighted, suggesting broader relevance beyond the study area.

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