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An assessment of Groundwater Vulnerability using the DRASTIC-LU Approach: A Case Study of the Mujib Basin, Jordan

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***Abstract*— Jordan is one of the world's poorest water possession, where groundwater is the fundamental supply. The Mujib Basin is one of Jordan's main aquifers where high-quality and quantity of groundwater is heavily exploited. Recently, industrial activities in the area (e.g., shale oil extraction, agriculture, and wastewater treatment) have called for studying the impact on groundwater resources. A modified DRASTIC method, coupled with GIS, was utilized to conduct a vulnerability study to evaluate the effect of land use on the Basin. This study considered all the possible cases of soil heterogeneity, land use, and hydrogeology. The traditional DRASTIC method provided values of 65–169 across the map and higher values of 70–200 by the modified version. However, the DRASTIC model is essential for creating a groundwater resource management system to maintain water quality. Provided maps are useful for identifying areas with high contamination risk to prioritize their protection and management.**

***Keywords*— DRASTIC, Mujib, oil shale, vulnerability.**

I. INTRODUCTION

Groundwater resources are considered a vital source of water, comprising more than 90% of the world's reservoirs of fresh water [2]. In addition, subsurface water is a paramount source of drinking water and water used in agriculture and industry, particularly in countries with low quantities of surface water, e.g., in Africa and the Middle East [6], [2]. There is a global consensus that groundwater resources are affected by climate change and socio-economic factors such as urbanization and various industries [20], [22], [5], [7]. Water quality analysis of unconfined aquifers is one of the more challenging issues in the field, where significant research has been conducted [21]. Jordan has an arid to semi-arid climate, with an annual rainfall of less than 200mm falling upon 92% of Jordan's area [17]. It is ranked as one of the poorest countries in terms of water supply; the demand for fresh water exceeds Jordan's available resources. Groundwater reserves form the main water resource in Jordan, meeting approximately 59% of the total demand [16]. In this research, the Mujib Basin (MB) is the selected study site. It is one of the major basins in Jordan, with a pumping rate of more than 82 MCM/year [16]. The reservoir is under stress and the annual groundwater extraction has surpassed the current designated safe yield [15]. Although more than 170 illegal wells, with uncontrolled pumping, have been demolished since 2017 in the MB area [16], there have been further impacts exacted by shale oil extraction, agricultural activities, and wastewater treatment.

The DRASTIC approach has been widely used to assess groundwater vulnerability due to environmental impacts through classification of a geographical area based on its susceptibility to groundwater pollution [23]. Reference [4] conducted a vulnerability study in the Lajjun area, using the Geologisches Landsamt method (GLA) method. The results revealed a high vulnerability in locations close to shale oil extraction, particularly in southern parts of Lajjun. In addition, Reference [19] undertook a DRASTIC study of groundwater vulnerability to shale oil extraction in the Lajjun Area. The results showed that this area is moderately vulnerable. Reference [3] examined the groundwater vulnerability of the Amman-Zerqa Basin (AZB). The DRASTIC model, integrated with the GIS tool, was used to delineate areas with a high potential for specific contamination. The aquifer and the geological structural settings proved to be highly vulnerable to agricultural pollutants, with one third of the AZB at moderate risk of pollution. Areas with high vulnerability to pollution are largely located in the centre of Amman old city.

Nevertheless, no such study has been conducted to evaluate the vulnerability of groundwater resources on the MB using a modified form of the DRASTIC method. The current study aims to provide vulnerability mapping of the MB to show the impacts of land use, using the DRASTIC model as a framework. This can provide a good insight into how the groundwater resources can be successfully managed. The study is outlined in four main sections. Section 1 provides an introduction to the study. Section 2 provides the proposed methodology, section 3 includes the research results and discussion and, finally, section 4 provides a conclusion.

II. RESEARCH METHODOLOGY

This chapter describes the major phases of the research undertaken, in which it aims to evaluate the effects of land use on the groundwater in the MB, Jordan. The overall approach

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consists of three sections. Section A includes site selection; section B includes data sources and section C includes the fully detailed methodology.

A. Site Selection

The proposed study area is the Mujib Basin (MB), located in central Jordan, with an approximate area of 6,600 km^2 [10]. It is a multi-terrain area, with varying contour elevations ranging from 1200m above sea level down to -420m below sea level [8]. The catchment area has a dry climate with an annual precipitation varying from 60 to 300mm [15]. The study area has a unique ecosystem and attractive biodiversity in the Mujib reserve, which is the lowest nature reserve in the world [18]. Springs in the basin form the main source of water for the Zara-Mae'n desalination plant, and the Mae'n thermal springs. Other significant areas include the Wala dam and the Mujib dam. The MB has diverse ground cover (Fig. 1), with bare soil comprising high percentage of whole surface area [10]. The Aquifer structure is complex, consisting of two main aquifer systems: (1) Amman Wadi Es Sir Aquifer (B2/A7), mainly formed of limestone, and (2) Kurnub/Ram Group Aquifer. Both aquifer systems are separated by low permeable aquitards (A1–A6) and Muwaqqar Chalk Formation (B3) [14].

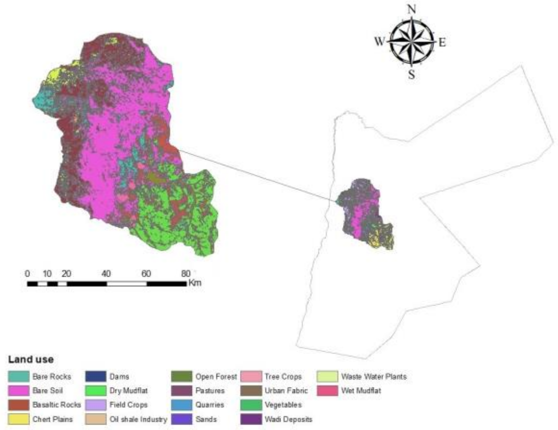

Fig. 1: Location of Mujib Basin catchment

B. Data Sources

A database has been collated using raw data sourced from local agencies, including the Ministry of Water and Irrigation (MWI) formed by the Water Authority of Jordan (WAJ), the Ministry of Environment (MoEnv) and the Ministry of agriculture (MOA), for the period 1984–2015. The main data parameters are monthly groundwater levels, hydraulic conductivity, daily and seasonal rainfall, soil types and topography.

C. The DRASTIC Method

DRASTIC is one of the most popular methods used to estimate groundwater vulnerability [1]. The DRASTIC model is composed of seven main parameters (Fig. 2), where each parameter refers to the impact of pollution on the groundwater aquifer [9]. DRASTIC stands for Depth of groundwater, Recharge, Aquifer, Soil, Topography, Impact of vadose zone, and hydraulic Conductivity. Each parameter has different weights and ratings (Table I). These ratings are assigned to different parameters based on their weight, and then the final DRASTIC index is calculated using this formula:

$$DI = (D_r * D_w) + (R_r * R_w) + (S_r * S_w) + (T_r * T_w) + (I_r * I_w) + (C_r * C_w) \qquad (1)$$

where, 'r' refers to rating and 'w' refers to parameter weight. Finally, the DRASTIC index was measured, and vulnerability values were classified (see Table III).

TABLE I

WEIGHTS AND RATINGS OF THE DRASTIC INDEX

Parameter	Weight	Value range	Rating
Depth to Water (m)	**5**	**0–1.5**	**10**
		1.5–4.5	**9**
		4.5–9	**7**
		9–15	**5**
		15–22.5	**3**
		22.5–30	**2**
		>30	**1**
Recharge (mm/yr)	**4**	**>254**	**9**
		178–254	**8**
		102–178	**6**
		51–102	**3**
		0–51	**1**
Aquifer Media	**3**	**Karst Limestone**	**10**
		Basalt	**9**
		Sand and Gravel	**8**
		Massive Limestone	**6**
		Massive Sandstone	**6**
		Bedded Sandstone, Limestone and Shale Sequences	**6**
		Glacial Till	**5**
		Weathered Metamorphic/Igneous	**4**
		Metamorphic/Igneous	**3**
		Massive shale	**2**
Soil Media	**2**	**Thin or Absent**	**10**
		Gravel	**10**
		Sand	**9**
		Peat	**8**
		Shrinking and/or Aggregated Clay	**7**
		Sandy Loam	**6**
		Loam	**5**
		Silty Loam	**4**
		Clay Loam	**3**
		Muck	**2**
		Non-shrinking & Non-aggregated Clay	**1**
Topography (%)	**1**	**0–2**	**10**
		2–6	**9**
		6–12	**5**
		12–18	**3**

		>18	**1**
Impact of the Vadose Zone Media	**5**	**Karst Limestone**	**10**
		Basalt	**9**
		Sand and Gravel	**8**
		Metamorphic/Igneous	**4**
		Sand and Gravel with significant Silt	**6**
		Bedded Sandstone, Limestone	**6**
		Sandstone	**6**
		Limestone	**6**
		Shale	**3**
		Silt/Clay	**3**
		Confining Layer	**1**
Hydraulic Conductivity (m/day)	**3**	**>82**	**10**
		41–82	**8**
		29–41	**6**
		12–29	**4**
		4–12	**2**
		0–4	**1**

III. MODIFIED DRASTIC (DRASTIC-LU)

To assess the effect of land use, an eighth parameter was added with corresponding ratings to the DRASTIC index as follows:

$$DI_{mod} = DI + (LU_r * 5) \qquad (2)$$

where DI_{mod} refers to DI modified, and LU stands for land use.

Land use rankings are classified and scored as follows: urbanization, industrial and agricultural activities have score of eight, vapor ponds a score of seven, with water, natural vegetation, and bare land rating of three, two and one, respectively.

IV. RESULTS AND DISCUSSION

A. DRASTIC Results

DRASTIC parameters were collected, analyzed, and overlapped to generate a groundwater vulnerability map.

1. Depth to groundwater: D represents the thickness of the layer before pollutants reach the top of the aquifer. The parameter was directly measured by subtracting the surface level from the top aquifer level for a 30-year period. The depths vary between 14–420m, with less vulnerability observed regarding ‘depth to water layer’.

2. Recharge: R refers to the net amount of water filtering into aquifers from neighboring water bodies. GIS spatial analyst tools were utilized to perform Piscopo's method to compute the net recharge [11]. Layers of precipitation, soil, and slope percentage degree were overlaid. According to DRASTIC ratings, the net groundwater recharge (GWR) layer indicates medium to high vulnerability.

3. Aquifer: stratigraphy data was obtained from MoEnv, where six main layers were identified. Silty loamy clay was predominant. Oil shale layers present a B3 formation (Table II).

TABLE II
CHRONOLOGICAL SEQUENCE OF LITHOSTRATIGRAPHIC UNITS OF MB [12]

Group	**Period**	**Lithology**	**Aquifer**
Belqa	**Quaternary**	**Dolomite, limestone, chert, Marl, clay and Kurnub**	**B2/A7**
Shihan Basaltic	**Tertiary**	**Dolomite, limestone, chert, Marl, clay and Kurnub**	**B2/A7**
Belqa	**Late Cretaceous**	**Dolomite, limestone, chert, Marl, clay and Kurnub**	**B2/A7**
Ajlun		**Marl, limestone, and dolomite**	**B2/A7**
Ajlun	**Early Cretaceous**	**Marl, limestone, and dolomite**	**B2/A7**
Kurnub Sandstone		**Varicolored sandstone, oil shale, marl and dolomite**	**Kurnub**
Ahaymir Volcanic		**Adamellite granite**	**Ram**

4. Soil: 16 different soil types were identified [13]. The soil layer forms the upper portion of the vadose zone, and the permeability of the soil can therefore directly affect the vulnerability value. The results show that limestone had a scored six and igneous soil a score of four. Both had increased the vulnerability to pollutants.

5. Topography: the topography map was generated from a contour map using GIS spatial tools to create surface slopes. Slight slope gradients (0–5%) with high vulnerability cover most of the area.

6. Impact of vadose zone: the unsaturated zone is mainly composed of limestone and some confining materials. Based on Table I, limestone scored the highest rating with a significant chance of contamination, which is likely to increase.

7. Hydraulic Conductivity: the values of hydraulic conductivity vary between $2.2x10^{-4}$ and $1.4x10^{-2}$ [14]. Limestone formation is predominant (Table II), with a high score.

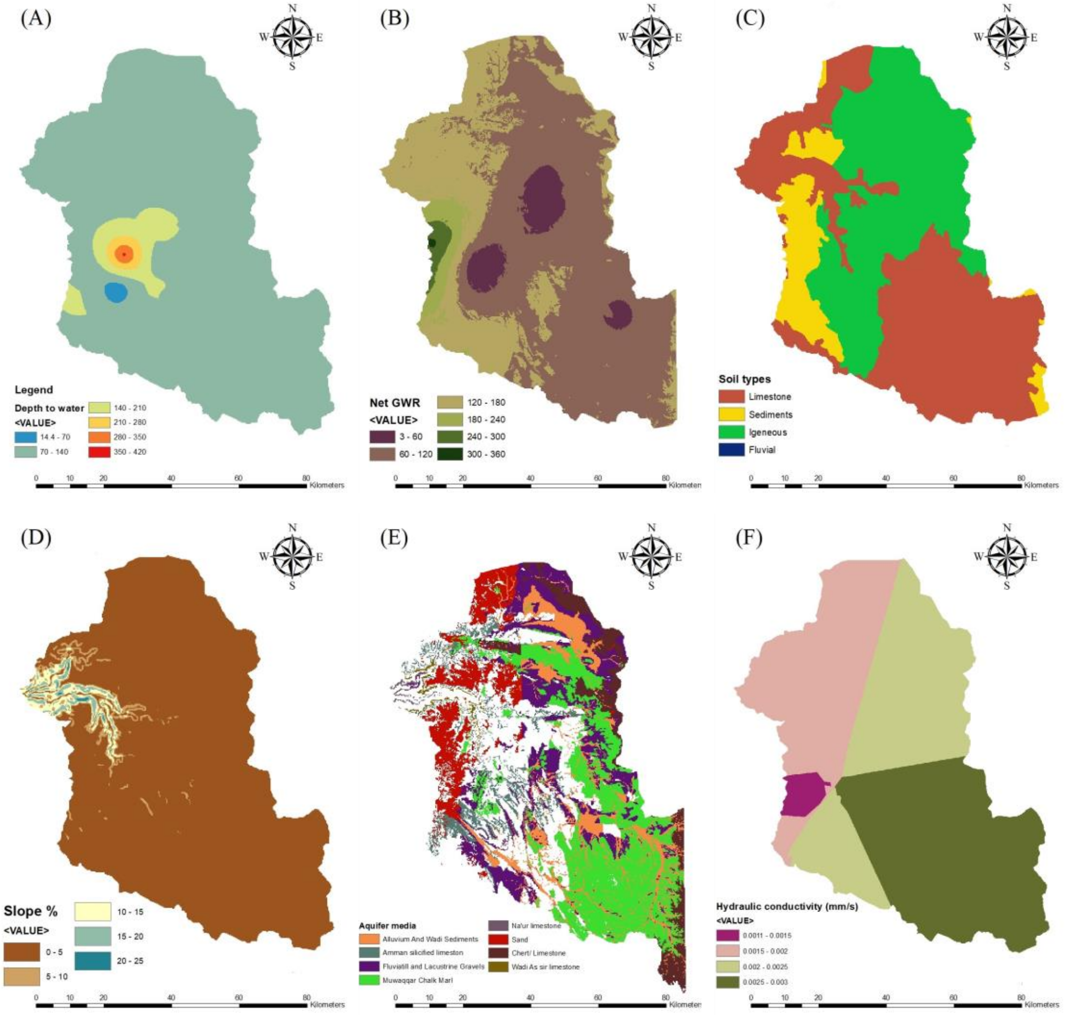

Fig. 2: DRASTIC parameters (A-F), (A) depth to water table, (B) net GWR, (C) main soil types, (D) slope degrees, (E) vadose zone effect, and (F) hydraulic conductivity

Referring to Table III, the DRASTIC index articulated that four ranges of vulnerability were recorded. Southern parts scored the highest vulnerability (150–180), followed directly by moderate to high degrees of vulnerability in most areas (Fig. 3). Areas of low vulnerability were recorded in scattered spots (65–90).

TABLE III
DRASTIC INDEX CLASSES

Vulnerability classes	**DRASTIC index**
Low	1–100
Moderate	101–140
High	141–200
Very high	>200

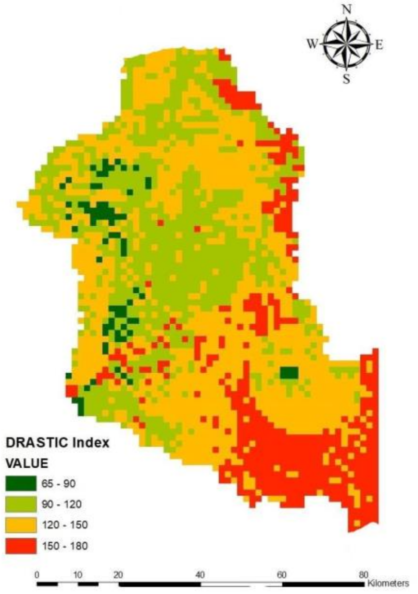

Fig. 3: Map of vulnerability according to DRASTIC Index

B. DRASTIC-LU results

A modified form of DRASTIC-LU was performed to evaluate the potential influence of land use. Shale oil extraction and wastewater treatment plants were both assigned to rating 8. The vulnerability map from the traditional DRASTIC index was then overlaid on the land use map (Fig. 1) to obtain a map of vulnerability based on land use. The modified DRASTIC-LU gave higher values of susceptibility to contamination, as northern and southern parts were the most vulnerable to land use practices (Fig. 4).

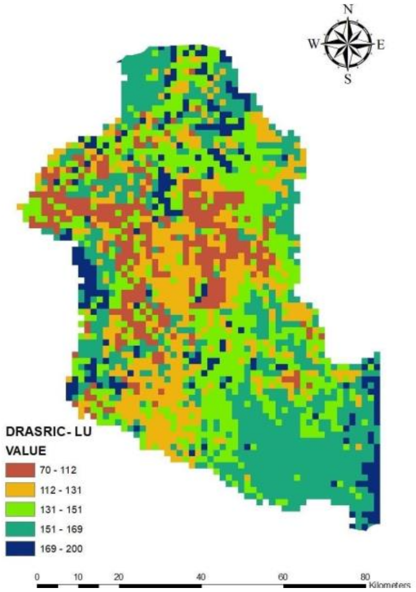

Fig. 4: Map of vulnerability according to DRASTIC-LU Index

V. CONCLUSION

The current study adopted the DRASTIC-LU index, along with GIS mapping tools, to assess the vulnerability of groundwater at the MB. The vulnerability map generated presented a minimum value of 70, and a maximum value of 200 in scattered areas. The overall index indicated high vulnerability in most areas, specifically in the extreme northern and southern parts of the study area. Surprisingly, most of the DRASTIC layers i.e., GWR, slope gradient, aquifer media, soil, and hydraulic conductivity were revealed to have a high vulnerability to the environment. It was found that the urbanization area achieved high vulnerability scores. The DRASTIC method might be considered as a helpful approach to qualitatively evaluate vulnerability to different sources of pollution, and to assist planners and decision makers in the preservation of groundwater resources. However, other quantitative, process-based models are recommended for precise outcomes.

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