

A modified modeling of potentiality and vulnerability of the groundwater resources in Amman Zarqa Basin, Jordan

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Abstract

This study aims at assessing the potentiality of groundwater resources in Amman-Zarqa Basin, North Jordan, in addition to the effect of vulnerability of groundwater within the catchment and building a multiple criteria method to manage artificial recharge process. This is one of the most important basins in Jordan, where most of the agricultural and industrial activities are located. The groundwater potentiality is determined using managed aquifer recharge (MAR) tool, along with other important tools to evaluate the sensitivity of groundwater, to pollution of the area under study. In order to ensure the quality of water that will be recharged in areas of high potential, vulnerability of groundwater is considered, while determining a suitable area in which to apply the MAR project. Under the geographic information system (GIS) environment, both groundwater vulnerability and MAR layers were prepared for the basin. MAR mapping showed very high and high potential areas, over 13% and 44% of the total basin area respectively, while low potential areas represented 14% of the total area. However, while evaluating groundwater vulnerability with MAR-produced map, very high and high potential areas of the managed aquifer recharge were found to be 8% and 29% respectively. For areas that have high and very high groundwater vulnerability, there is no scope to apply MAR project in 44% of the total area. The final results indicate importance of applying the studies together, in order to better enhance the results of MAR method, as there might be areas with high MAR potentiality and vulnerability rates within the same areas, which will eliminate the ability of the areas to be used as potential recharge areas.

Keywords: Amman-Zarqa Basin (AZB); DRASTIC index; groundwater potentiality; groundwater vulnerability; managed aquifer recharge (MAR).

1. Introduction

Amman Zarqa Basin (AZB) is one of the most developed areas in Jordan. Groundwater represents the main source of water supply in the basin. Most of the groundwater exists in and is being extracted from the Basalt and Amman-Wadi Sir (B2/A7) aquifers. The outcrop areas include highest concentration of wells, where depletion and deterioration in water quality have reached critical stages (see Figure 1). Within Amman-Zarqa Basin, the most important aquifer is Amman-Wadi Sir (B2/A7) system (BGR and WAJ, 1994). In late 70s and early 80s, decline in water levels in the basalt and in the B2/A7 aquifer in different areas were noticed in both government and private wells in the basin. Both the extent and the annual rate of decline vary considerably. The decline in water levels of the B2/A7 aquifer range between 0.67m and 2.0m per year (MWI, 2010). The amount of rainfall is mainly governed by the topography and precipitation in the study area, that ranges from 500 millimeters per year (mm/yr) to less than 50 mm/yr, producing an average amount of 718 million cubic meters (MCM) per year, according to the Jordan Meteorological Department (Figure 2). The runoff coefficient in the basin is about 3%, where generated runoff averages a volume of 21.5 MCM per year. Hydro-geologically, there are three main aquifers in the study area: the B2/A7 limestone, basalt, and alluvial aquifers. Figure 3 shows the distribution of these aquifers in the study area. Between these aquifers many aquitards are found, which minimize the possibility of applying any MAR project in the area. In addition, the presence of the alluvial aquifers enhances MAR projects.

2. Methodology

Potentiality of the groundwater refers to expected value of the aquifer to yield groundwater. The term “artificial recharge” has also been used to describe this process. The term MAR was introduced by Bouwer (2002), to replace the previously used term “artificial recharge” and to describe the intended and controlled recharge. MAR projects are important for arid to semi-arid areas because of their ability to increase the amount of stored groundwater and to recover the over-exploited groundwater in addition to ability to improve quality of groundwater during recharge and self-purification process. Reducing loss of fresh surface water, as a result of exposure to evaporation is of vital importance to MAR Ismail *et al.* (2010).

In order to evaluate MAR potential for the aquifer on a detailed scale within the study area, four thematic layers are important and they interact with each other to produce the final MAR map. These factors are: hydro-geological classification (which controls the presence or absence of groundwater aquifers to be recharged), slope classification of the study area (which is an important factor as the topography is one of the most effective factors that drives the recharge process), urban area distribution (which is another factor that must be taken into consideration during the building of MAR

projects - a buffer zone around the urban area must also be taken into consideration) and finally the proximity to the water resources (which will be collected and used for the recharge process).

According to Hobler & Subah (2001), the major distribution of the hydro-geological units in Jordan was modified by the Natural Resources Authority in 1:50000 geological maps and used to evaluate the primary potentiality. This map shows that the study area was subdivided into two main hydro-geological layers (Figure 3): the aquifer unit composed of B2/A7 and the basalt aquifer. These are considered as the main aquifers in the study area and the aquitard units, which are composed of impermeable rock units. MAR only has a potential along aquifer outcrops.

Topography plays a major role in MAR through infiltration, as the slope determines the residence time of surface water over a specified area. According to Rapp (2008), the most effective slope for MAR is 0–5 %, under which proper infiltration process can take place without any enhancement for runoff. Regarding slopes, the area was subdivided into two slope classes: from 0 to 5% (which is suitable for MAR) and greater than 5% (which is unsuitable for MAR).

Urban areas and small settlements distributed over the study area represent a limitation for MAR, as MAR requires an appropriate area and some construction works. However, other types of land use such as farms do not restrict MAR constructions. A map for the urban areas as obtained from the Ministry of Water and Irrigation was used in order to determine the thematic layer with a buffer of 250 meters around urban areas.

According to Gale (2005), the water sources suitable for MAR are: perennial streams, rivers or canals, intermittent streams, wadis and flood flow water, treated and reclaimed water and desalinated water. Maps for these components are drawn, with a buffer zone of 5 kilometers around dams and waste water treatment plants included. The drainage system for the area under study was designed using Arc Hydro tool under the environment of Arc GIS. Then a buffer of 250 meters around these lineaments (which is considered an economic distance for MAR) was drawn.

The DRASTIC index is one of the vulnerability indices that could be applied in Jordan because of its applicability on climatic conditions, aquifer distribution and aquifer settings. In addition to that, the DRASTIC index has been selected according to its wide variation of parameters that really affect the groundwater system in any environment. In this model (DRASTIC), spatial datasets on depth to groundwater, recharge by rainfall, aquifer type, soil properties, topography, impact of the vadose zone and hydraulic conductivity of the aquifer are combined to assess the vulnerability of aquifers to surface activities (Table 3) (Engel *et al.*, 1996). The following equation

governing DRASTIC index DI was defined by Knox *et al.* (1993); Fortin *et al.* (1997) and Fritch *et al.* (2000):

$$DI = DrDw + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw$$

DRASTIC index in the equation above is considered as an indicator for pollution potential. The effect of different parameters on groundwater vulnerability has been described by Piscopo (2001).

For building the groundwater vulnerability map, different environmental parameters, which interfere while anticipating amount and location of impurities, that may affect the aquifers, were taken into consideration. Groundwater settings, hydrological and hydro-geological conditions, land use parameters, environmental issues, soil parameters and other elements, which may vary from one aquifer to another and from one area to another were used to determine the vulnerability of groundwater (Vrba & Zaporozec, 1994). The different spatial parameters of the aquifer as obtained (geology, recharge, water table, soil texture, etc.) were exported into GIS, and the equation for calculating groundwater vulnerability with DRASTIC Index were used to deduce different vulnerability classes.

3. Results

For processing of the MAR map, Table 1 shows the potentiality of the area under study to be used for aquifer recharge. Applying data in the pattern shown in table, resulting map is shown in Figure 4.

In Jordan, several vulnerability studies were conducted using different indices. In Azraq basin, the area bordering AZB from the east, DRASTIC index and MAR were applied separately. The results show that the areas are with different ranges of vulnerability rates according to the environmental settings, as described by Jasem & AlRaggad (2010), while the MAR within the same basin defines the area with the high potentiality of recharging the groundwater as shown by AlRaggad & Jasem (2010). From the two studies, it is clear that there are some high recharge potential areas with a range of high groundwater vulnerability rates, which must be removed from the potentiality map because of its ability to pollute groundwater.

Table 1. Combination of classified slope and hydro-geological classes and potential zones (Rapp, 2008)

Combination of classified slope and hydro-geological classes		
MAR parameters	MAR Potential	
Aquifer and slope <5%	High	
Aquifer and slope >5%	Medium	
Enhanced aquifer and slope <5%	Very high	
Enhanced aquifer and slope >5%	Medium	
Aquitard and slope <5%	Low	
Aquitard and slope >5%	Low	

Parameters combination and the resulting potential zones		
MAR parameters	Proximity to water sources	MAR potential
Aquifer and slope <5%	No	High
Aquifer and slope <5%	Yes	Very High
Aquifer and slope >5%	No	Medium
Aquifer and slope >5%	Yes	High
Enhanced aquifer and slope <5%	No	Very High
Enhanced aquifer and slope <5%	Yes	Excellent
Enhanced aquifer and slope >5%	No	Medium
Aquitard and slope <5%	No	Low
Aquitard and slope >5%	No	Low

As shown in Figure 4, the area under study contains higher MAR areas in outcropped aquifers that have gentle slopes and higher proximity to water resources. Percentages of areas that are suitable for MAR projects in AZB are shown in Table 2.

Table 2. Percentages of MAR classification within the study area

MAR potentiality	Area %
Very high	13
High	44
Moderate	28
Low	15

Applying the process in Table 3 produces a vulnerability map that describes the ability of the aquifer to be polluted in the AZB is shown in Figure 5. Areas with aquitards are excluded from the vulnerability map, as this map refers to groundwater. Also, areas in western parts of the study area, in addition to some separated areas in the western parts, are higher vulnerability areas. This could be reasoned by the depth to the water table in each aquifer, which plays a vital role in assuming vulnerability values. In addition to the depth to water table, different parameters play major roles in the vulnerability assessment.

Table 3. DRASTIC index method for assessing groundwater vulnerability (Aller *et al.*, 1987).

Parameter	Range	Rating	Relative weighting
Depth to water (D)	0-2 m	7	5
	2-5 m	6	
	5 -9 m	5	
	9-15 m	4	
	15-23 m	3	
	23- 30 m	2	
	> 30 m	1	
Recharge by rainfall	3	1	4
	4	2	
	5	3	
	6	4	
	7	5	
	8	6	
Aquifer media (A)	9	7	3
	Massive shale	2	
	Metamorphic/igneous	3	
	Weathered met./igneous	4	
	Bedded sandstone, Limestone,	6	
	Shale sequences	6	
	Massive sandstone	6	
	Massive limestone	6	
	Sand and gravel	8	
	Basalt	9	
Karst limestone	10		

Soil media (S)	Soil thin or absent	10	2
	Gravel	9	
	Sand	8	
	Peat	7	
	Shrinking and/or aggregated clay	4	
	Sandy loam	5	
	Loam Silty loam	4	
	Clay loam	3	
	Muck	2	
	Non-shrinking and non-aggregated clay	1	
Topography (T)	0-2%	7	1
	2-6 %	6	
	6-10%	5	
	10-16%	3	
	16-25%	2	
	>25%	1	
Impact of vadose zone	Confining layer	1	5
	Silt/clay	3	
	Shale	3	
	Limestone	6	
	Sandstone	6	
	Bedded limestone, sandstone shale	6	
	Sand and gravel with significant silt & clay	6	
	Metamorphic / igneous	4	
	Sand and gravel	8	
	Vesicular basalt	9	
Karst limestone	10		
Hydraulic conductivity	$0.50 \cdot 10^{-6} - 0.50 \cdot 10^{-4}$	1	3
	$0.50 \cdot 10^{-4} - 0.15 \cdot 10^{-3}$	2	
	$0.15 \cdot 10^{-3} - 0.36 \cdot 10^{-3}$	4	
	$0.36 \cdot 10^{-3} - 0.51 \cdot 10^{-3}$	6	
	$0.51 \cdot 10^{-3} - 0.10 \cdot 10^{-2}$	8	
	$> 0.10 \cdot 10^{-2}$	10	

A merging step, which is a combination of both groundwater vulnerability and final MAR project mapping, was done assuming that areas with high and very high vulnerability classes should not be used for MAR projects. Hence, the final map excludes areas with high vulnerability classes (Figure 6).

After taking the vulnerability classes into consideration, the percentage of areas available for applying MAR, changed as listed in Table 4. Areas not suitable for MAR works out to 44% of the total area; 8% and 29% are very high and high MAR potential areas respectively.

Table 4. Managed aquifer recharge areas percentage distribution after adding the vulnerability classes.

MAR potentiality	Area %
Very high	8
High	29
Moderate	17
Low	2
Not suitable	44

4. Conclusion

Both, managed aquifer recharge and vulnerability concepts are very important to be applied for arid to semi-arid areas. The importance comes from the significance of groundwater as the main resource of water in these areas. Jordan, being one of the countries, poorest in water resources, puts more pressure on these groundwater resources. The need to save existing water resources highlights the value of the groundwater vulnerability concept, and the importance of providing renewable groundwater resources increases the importance of managed aquifer recharge concept.

Merging both these concepts together is a new procedure to limit areas that should be considered as potential areas for applying and building national water projects to save and enhance existing water resources in Jordan.

This article shows that combining MAR and vulnerability map together reduces potential areas of groundwater resources that might be used for such projects. Also, this will save existing resources from pollution.

Areas that show high and very high potentiality for managing aquifer recharge concept without vulnerability mapping were a total of 75% of the study area, while this figure was reduced to 38% of the total area from the basin, after eliminating areas classified as high vulnerability.

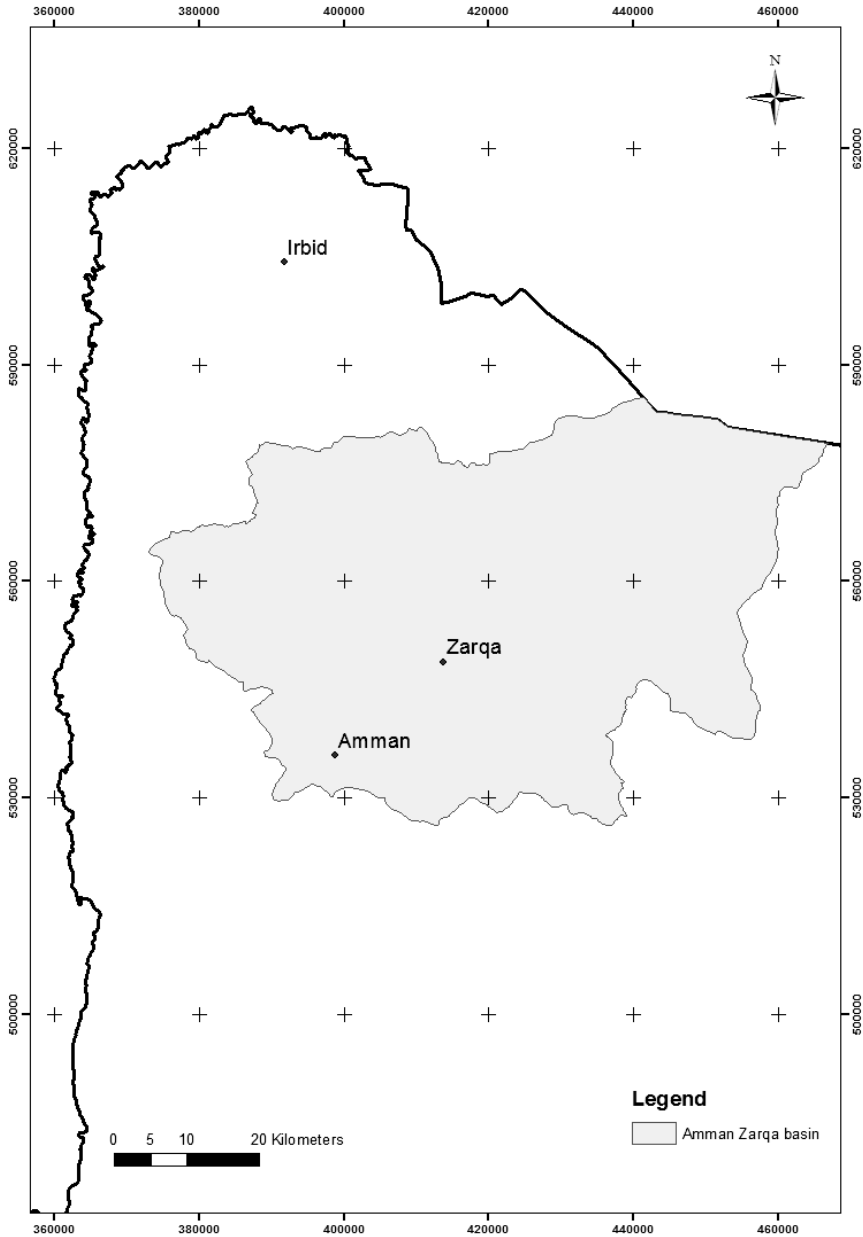


Fig. 1. Location map for the Amman Zarqa Basin in Jordan.

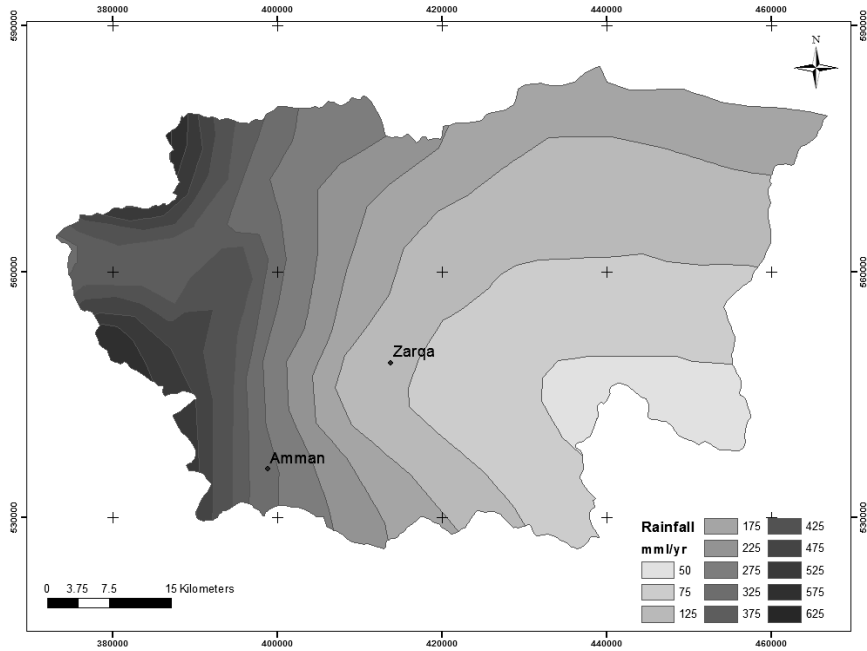


Fig. 2. Isohytal map for the rainfall distribution in Amman Zarqa Basin.

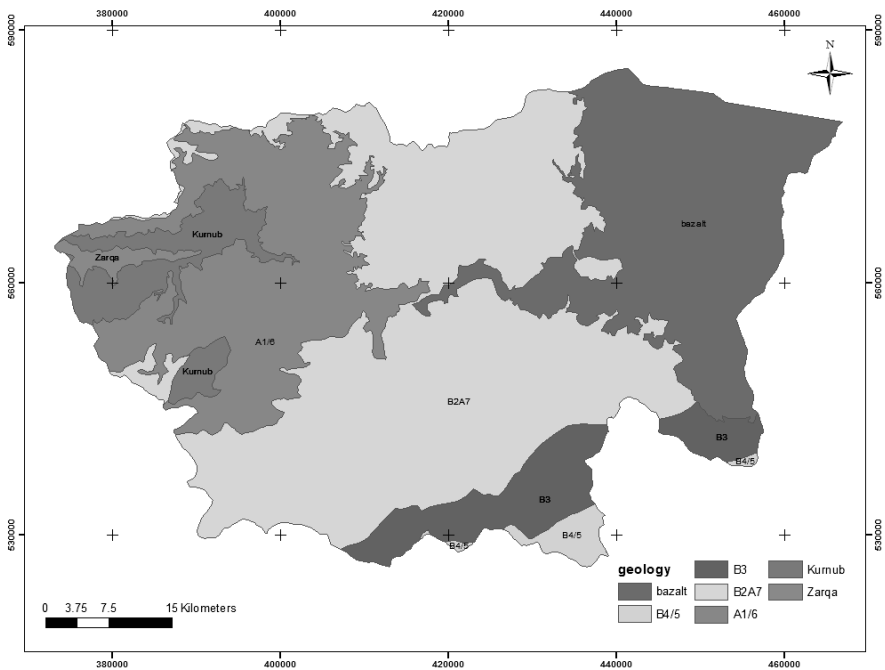


Fig. 3. Hydro-geological distribution of aquifer and aquitards outcropped in the study area.

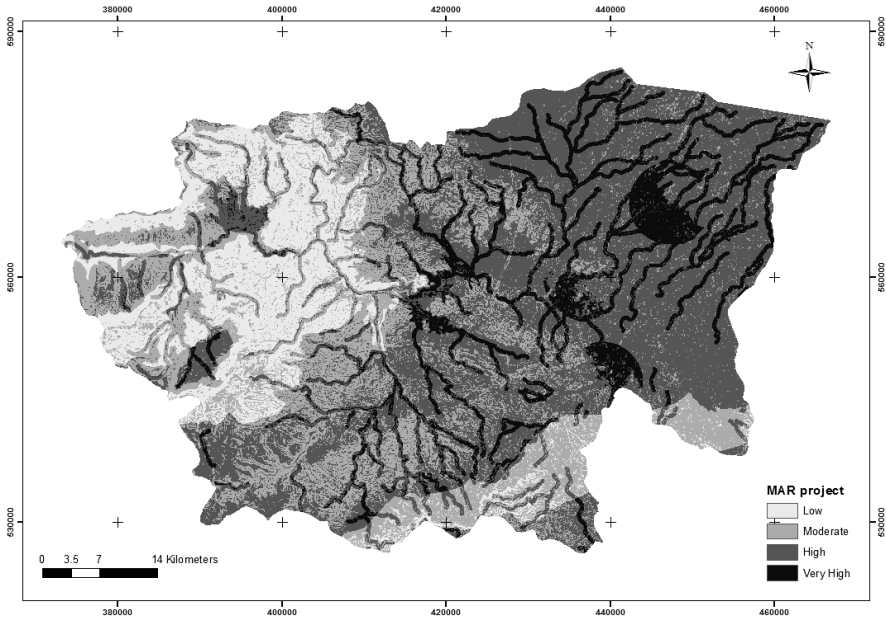


Fig. 4. Managed aquifer recharge final map for AZB.

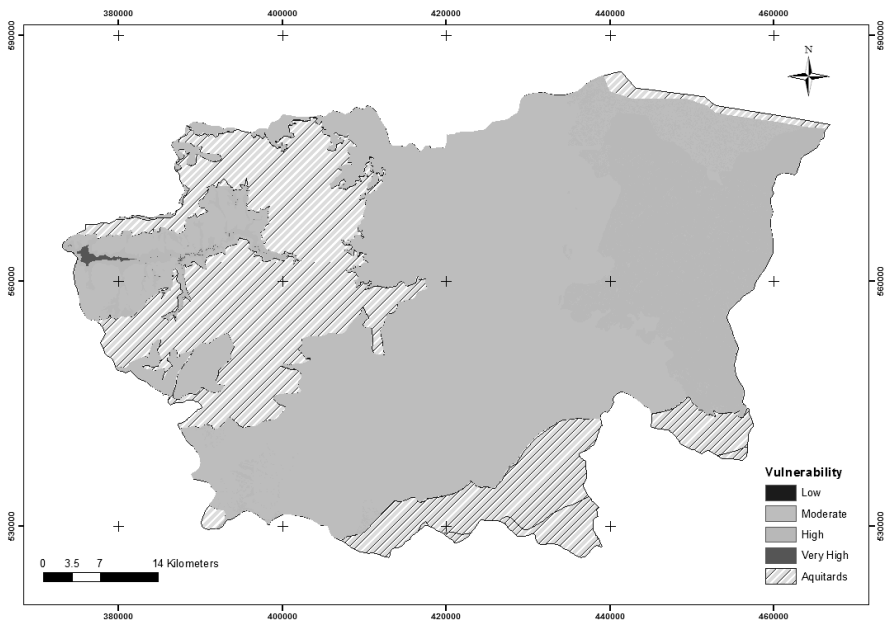


Fig. 5. DRASTIC index groundwater vulnerability map for the aquifers in AZB.

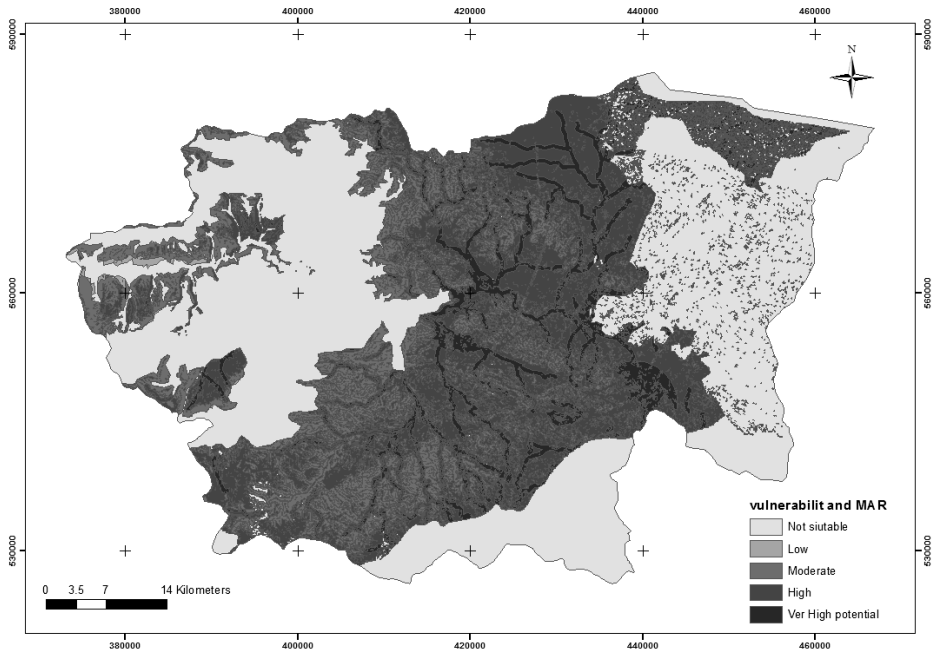


Fig. 6. A combined MAR and DRASTIC index vulnerability map for AZB.

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نمذجة مطورة لدراسة إمكانية تواجد المياه الجوفية وقابليتها للتلوث في منطقة حوض عمان الزرقاء الجوفي - الأردن.

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خلاصة

تهدف هذه الدراسة إلى تقييم الموارد المائية الجوفية في حوض عمان الزرقاء، شمال الأردن، إضافة إلى تأثير قابلية المياه الجوفية للتلوث داخل هذه الخزانات الجوفية وبناء نموذج لإدارة عملية التغذية الاصطناعية. حوض الزرقاء هو واحد من أهم الأحواض المائية الجوفية في الأردن حيث توجد معظم الأنشطة الزراعية والصناعية في منطقتها. يتم تحديد إمكانات المياه الجوفية باستخدام إعادة شحن المياه الجوفية المدارة عن طريق نظام (MAR). تتم نمذجته إضافة إلى أداة هامة أخرى لتقييم حساسية المياه الجوفية للتلوث في منطقة الدراسة، وهي تبين المياه الجوفية لتحديد منطقة مناسبة التي لتطبيق المشروع MAR من أجل ضمان جودة المياه التي سيتم شحنها في المناطق المستهدفة. باستخدام نظم المعلومات الجغرافية، أظهرت الخرائط MAR المجالات المحتملة عالية جدا وعالية أكثر من 13% و 44% من المساحة الكلية للحوض على التوالي، في حين تمثل المناطق المحتملة منخفضة 14% من المساحة الكلية. ولكن عند تقييم دراسة إمكانية تأثر المياه الجوفية مع خريطة إنتاجها MAR وهي المجالات المحتملة عالية جدا وعالية لإعادة شحن المياه الجوفية تمكنت تصبح مساوية لـ 8% و 29%، والمناطق التي لديها حساسية شديدة ولا يوجد أي مجال لتطبيق مشاريع MAR في 44% من المساحة الكلية، النتائج النهائية تشير إلى أهمية تطبيق الدراسات معاً من أجل تعزيز أفضل إعداد للنتائج طريقة MAR كما قد تكون هناك مناطق مع ارتفاع احتمالية MAR ومعدلات احتمالية التلوث العالية في نفس المناطق التي سيتم استثناء المنطقة لاستخدامها المجالات المحتملة لعمليات إعادة الشحن للمياه الجوفية.