PAN
POLSKA AKADEMIA NAUK
JOURNAL OF WATER AND LAND DEVELOPMENT
e-ISSN 2083-4535
ITP-PIB
Polish Academy of Sciences (PAN)   Institute of Technology and Life Sciences – National Research Institute (ITP – PIB)

JOURNAL OF WATER AND LAND DEVELOPMENT
DOI: 10.24425/jwld.2024.149112
2024, No. 60 (I–III): 100–111

Application of the fuzzy analytic hierarchy process for water resources in the Wadi AlHasa catchment, Jordan

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RECEIVED 18.06.2023   ACCEPTED 03.01.2024   AVAILABLE ONLINE 22.03.2024

Abstract: This article introduces a groundwater vulnerability assessment model that utilises the fuzzy analytic hierarchy process (FAHP) in the Wadi AlHasa catchment, Jordan. The assessment takes into account both geomorphological and hydrogeological variables, employing a comprehensive methodology that integrates various parameters. To evaluate the catchment, the study employs remote sensing and Geographic Information System (GIS) techniques. The analysis of the digital elevation model enables the creation of a map illustrating the diverse geomorphology of the catchment. This geomorphology significantly influences drainage density, direction, and the spatial distribution and intensity of flash flood events. Moreover, the study develops and maps a fuzzy FAHP DRASTIC vulnerability index, which proves to be a valuable tool for assessing the susceptibility of groundwater resources to contamination. The unique feature of the index is its ability to incorporate uncertain or subjective data, providing a means to evaluate the significance of various influencing factors. This information serves as critical support for decision-making and management efforts geared towards safeguarding and enhancing groundwater resources. Within the study area, the DRASTIC vulnerability index values span from 0.08325 to 0.28409, with 18% of the site exhibiting a high vulnerability rate. Additionally, the article implements a managed aquifer recharge model (MAR), with 31% of the area falling into MAR classes. Among these, 22.1% are classified as a high MAR class, while 0.7% belong to a very high MAR class. These findings underscore the feasibility of MAR projects in regions with limited water resources.

Keywords: DRASTIC index, flash floods, fuzzy analytic hierarchy process (FAHP), geomorphological units, groundwater vulnerability, managed aquifer recharge (MAR)

INTRODUCTION

Climate change has significant implications for water resources in arid and semi-arid regions, presenting challenges for decision-makers responsible for water management. The sustainable development of groundwater resources requires the implementation of diverse approaches, and hydrogeological models tailored to specific environmental conditions and factors affecting the targeted area (Filippis *et al.*, 2019). Arid and semi-arid regions are particularly susceptible to environmental pressure in terms of water resource sustainability and management. These regions face a high dependence on limited water resources, exacerbating the vulnerability of their water systems (Trondalen, 2009). Uncontrolled or haphazard urbanisation and human activities further intensify stress on hydrological systems, exerting considerable pressure on water resources in terms of demand and management.

Various hydrological phenomena have been studied to understand the changes and impacts associated with these activities. Across the globe, numerous models have been developed to assess hydrology and climate-soil interactions, each with its own unique components (Lababneh, Al Kuisi and

Al-Bilbisi, 2019). It is essential to consider hydrological characteristics related to land use, soil properties, and slope when estimating runoff depth using the runoff coefficient. These factors provide valuable insights into the hydrological processes and dynamics of the region (Lababneh, Al Kuisi and Al-Bilbisi, 2019). From a climate perspective, a decline in rainfall is often correlated with increasing temperatures and decreasing relative humidity, highlighting the complex interplay between climate variables and water resources (Abu Isleih *et al.*, 2020). The development of the geospatial technique enhances the understanding of complicated and heterogeneous hydrological systems (Zhou and Li, 2020). The use of the Geographic Information System (GIS) to create drainage systems based on digital elevation models (DEMs) offers a robust analytical tool. Representation of hydrological catchment areas, overlaying maps, and outline foundations of GIS tools help convert hydrologic parameters from input data to output results. The hydrological examination tool in ArcGIS helps researchers explore water fluctuation over a specific surface area (Zhao *et al.*, 2009) Many researchers have applied remote sensing (RS) models parallel with GIS methods in flood risk cases (Khalil, 2017). Moreover, researchers enhanced techno learning algorithms' interpretation with many optimisation algorithms (Costache *et al.*, 2020). Understanding the characteristics of high-relief topography and geomorphological units can be important for managing water resources, as these factors can influence the availability and quality of water in a given area. Jordan's high relief land topography is mainly affected by the Dead Sea Transform fault. In the meantime, the topography in Jordan designed climatic patterns with several hydrologic landscape systems (Odeh and Mohammad, 2020). High-relief topography and geomorphological units can have important impacts on the movement and distribution of water in the landscape.

For example, in high-relief topography, water is often channelled through narrow valleys or streams, which can lead to increased erosion and sedimentation. Geomorphological units can also affect the movement of water, as different units may have different levels of permeability and infiltration. This can influence the amount of water that is able to percolate into the ground and recharge aquifers. Geospatial approaches have been instrumental in conducting hydrogeological analysis of groundwater resources, enabling effective assessment of water management in Jordan (Al-Bakri *et al.*, 2016; Odeh *et al.*, 2020). Geomorphological units are divisions of the landscape that are defined by their geological and physical characteristics, such as their rock type, slope, and erosion patterns. These units can be identified based on factors such as the age of rocks, processes that formed them, and the vegetation.

Overlay techniques usually interpret groundwater vulnerability to discover pollutants' ability to access the target aquifer. This process can help decision-makers to mark pollution areas that spoil groundwater aquifers due to human activities (Mohammad, 2017). However, groundwater vulnerability deals mainly with the hydrogeological context, rather than pollutant attenuation. Hazard mapping depends on the integration of groundwater vulnerability mapping and aquifer classification. Therefore, the higher vulnerability levels align with porous aquifers due to the permeable nature of the rock. This increases the hydraulic conductivity and then the pollutant transfer through groundwater basins. Aquifers with coarse-grained sediments and fissured characteristics can be associated with medium vulnerability levels. Lower vulnerability classes were found in poor permeability areas in non-aquiferous media (Mohammad *et al.*, 2018; Nistor, 2020). Therefore, this study was developed to report on the vulnerability of aquifers within the study area using the DRASTIC method and the GIS tool. Furthermore, the FAHP analytical method was applied to determine different parameters rates factors in the targeted approach; then results were mapped using the GIS. It is vital to examine many environmental parameters to generate a groundwater vulnerability map, groundwater settings, hydrological circumstances, land use conditions, environmental concerns, and soil factors. In the FAHP approach, the determination of criteria weights relies on various comparisons by domain experts. These experts use their subjective judgments to establish weight ratios, which are expressed as triangular fuzzy numbers. This methodology gives greater importance to judgments based on higher confidence levels by domain experts. In this process, definite values are converted into fuzzy numbers and membership functions based on expert opinions. This approach allows for a more reasonable evaluation of criteria weights, leading to better decision-making outcomes (Aryafar, Yousefi and Ardejani, 2013; Tan *et al.*, 2013; Sresto *et al.*, 2021).

The managed aquifer recharge (MAR) is a water management strategy aimed at optimising natural water storage and enhancing the resilience of water supply systems, particularly in times of reduced flow and heightened seasonal fluctuations, such as dry seasons. In the MAR, aquifers are deliberately refilled to replenish water resources. This controlled recharge process prioritises the mitigation of health and environmental risks. The acronym MAR was recently established by Bouwer (2002) to displace the artificial recharge and explain the advanced and affected groundwater recharge. MAR projects are required for arid and semi-arid areas due to their capacity for improving the volume of groundwater saved. The MAR presents a crucial adaptation path for developing countries grappling with water variability and scarcity. The goal of the MAR is to increase the volume of water deposited in the aquifer, which can help to reduce the impact of droughts, reduce demand on surface water sources, and improve water quality by removing contaminants from water before it is introduced into the aquifer. Besides, this can enhance the groundwater quality through recharge and self-purification. Reducing the fresh surface water loss due to evaporation plays a crucial role in the MAR (Ismail *et al.*, 2010; Mohammad *et al.*, 2016).

An interactive model that integrates both the groundwater vulnerability and the managed aquifer recharge (MAR) project maps can be important for several reasons. Some of the potential benefits of the model include decision-making support; the combined model can be used to support decision-making by providing a way to analyse the potential benefits and costs of different MAR projects, based on their locations and levels of groundwater vulnerability in the surrounding area. The planning and management process; the model can be used to support planning and managing MAR projects by identifying areas where the MAR may be particularly effective, and providing a way to monitor the performance of existing MAR projects. The model could be important for communication; it provides a useful tool for communicating information about MAR and groundwater vulnerability to policy makers and water resource managers.

MATERIALS AND METHODS

STUDY AREA

Wadi AlHasa is a significant water source in the southern Dead Sea basin area, one of the most limited water basins in terms of its water resources (Abu Salim, 2014) – Figure 1; it covers an area roughly 2520 km^2 of high-relief topography. The Wadi AlHasa catchment is described mainly by dry weather conditions, based on the annual average rainfall in the region around 128 mm. Additionally, the area is characterised by high evaporation rates attributable to its elevated temperature levels; the annual average for evaporation reached more than 3500 mm. The monthly evaporation rate in the AlHasa station is estimated to reach 100 mm in winter season in December, and 500 mm in the hot summer in July. The annual average temperature is 19.5°C, which is the reason for a high loss of rainfall. Wadi AlHasa is fed by several smaller streams and tributaries that drain the surrounding mountains, and it is a key water resource in the region. It is known for its rich agricultural land, which is irrigated by water from the Wadi. It also supports a diverse ecosystem, including a variety of plant and animal species. In recent years, Wadi AlHasa has faced a number of challenges related to water management; these challenges include over-abstraction of water from the wadi. Consequently, this phenomenon has resulted in draining of groundwater and drying up wadi itself in some areas. There have also been concerns about the quality of water in the basin, as it is vulnerable to contamination from agricultural runoff and other sources. Efforts are underway to address these challenges and to better manage the water resources of Wadi AlHasa; these efforts include measures to improve water conservation and efficiency, as well as efforts to protect and restore the ecological integrity of the basin.

Wadi AlHasa has almost permanent drainage flow exclusively downstream, where surface elevation is less than 400 m (Abu Salim, 2014). Geologically, rocks in the study area are of different periods and types; the units are defined according to their hydrogeological characteristics and the ability to permit water. To better explain the probability and intensity of flash flooding in this area and inform decision-makers on flood mitigation measures, it is crucial to perform a geomorphological evaluation of the AlHasa catchment area. Therefore, it is necessary to create an analytical hydrological model to correlate hydrological units' location with geomorphological units and determine their relationship. In parallel, this paper also evaluates the basin's groundwater vulnerability to better protect groundwater in the targeted area (Abu Salim, 2014).

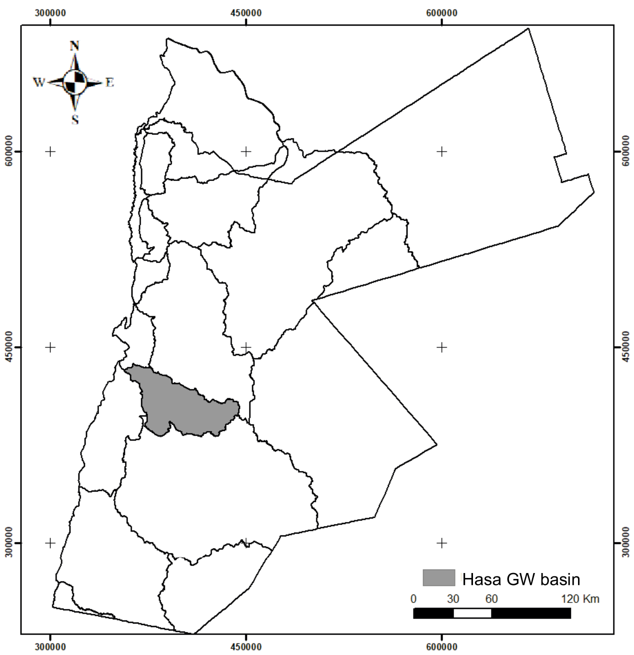

Fig. 1. Location of study area in Jordan; source: Ministry of Water and Irrigation MWI (2023), open source

HYDROLOGICAL AND CLIMATE MODELLING

Hydrological and climate modelling is important for understanding and predicting the behaviour of water and the Earth's climate system. The modelling uses mathematical equations and data from various sources, such as meteorological observations and satellite measurements, to simulate and analyse processes that govern the movement and distribution of water on Earth. Hydrological models are used to study the water cycle and the movement of water through the environment, including interactions between the atmosphere, land surface, and groundwater. These models can be used to predict how much water will be available in a particular region, how it will be distributed, and how it will be affected by land use practices and climate change. Hydrological and climate modelling plays a vital role in numerous applications, encompassing water resource management, flood forecasting, agricultural planning, and climate change research.

Topography factor was determined through land surface elevations within heights arrayed in the DEM; the GIS technique uses several data visualisation tools (Wang and Yin, 1998).

The hydrology toolbox in ArcGIS 10.7 and the spatial analyst extension were employed to derive the drainage network that overlay the aquifer for the proposed analytical model.

Evapotranspiration is a very strong factor in hydrological modelling. In some conditions, the average evapotranspiration might reach more than 80% of the total annual rainfall. Involving the original Penman–Monteith equation, aerodynamic equations, and surface resistance, the FAO developed a new equation "Penman–Monteith method" to estimate *ETo* (Allen *et al*., 1998); the equation is described as follows:

$$ETo = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273}(e_s - e_a)u_2}{\Delta + \gamma \cdot (1 + 0.34u_2)} \tag{1}$$

where: ETo = evapotranspiration (mm·d^{-1}), R_n = solar radiation at the crop surface (MJ·m^{-2}·d^{-1}), G = heat flux from soil (MJ·m^{-2}·day^{-1}), T = mean air temperature at 2 m height (°C), u_2 = wind speed at 2 m height (m·s^{-1}), e_s = saturation vapour pressure (kPa), e_a = actual vapour pressure (kPa), Δ = slope vapour pressure curve (kPa·°C^{-1}), γ = psychrometric constant (kPa·°C^{-1}).

Different input data for the equation were determined from studies of the area from MWI and literature.

A groundwater recharge conceptual model is a simplified representation of processes that control the movement of water in and out of an aquifer. These models are used to help understand how groundwater recharge occurs and how it is guided by multiple factors, including climate, geology, land use, and human activities. A groundwater recharge conceptual model typically includes different components which are vital in estimating the groundwater recharge; starting with surface water sources. These are the sources of water that can recharge the aquifer, and include rivers, lakes, and precipitation. In the case of Wadi AlHasa, the precipitation is the primary water source within the basin.

The recharge zone is another important component in the model; it includes areas where surface water is capable to penetrate the ground and recharge the aquifer. The zone comprises the aquifer itself, its properties and conditions within the targeted basin. Moreover, discharge areas arte those where water is able to flow out of the aquifer and can be used or discharged into the environment, e.g. through springs or wells. Groundwater recharge conceptual models can be useful for understanding factors that influence groundwater recharge and predicting changes and how these factors may affect the availability of groundwater in the future.

Recharge is essential in assessing groundwater resources; simple water balance formulas are usually applied to evaluate groundwater recharge, calculated using a simple water balance equation which was developed in the 1940s by Thornthwaite (1948):

$$R = P - (E + FF) \tag{2}$$

where: R = recharge (mm), P = precipitation (mm), E = evaporation (mm), FF = flood flow (mm).

This groundwater recharge model is described and does not exactly examine the land cover and landforms' impact. However, it could recommend groundwater recharge zones (Odeh *et al.*, 2009).

The DRASTIC index is part of a method for evaluating the vulnerability of groundwater to contamination. It was developed by the United States Environmental Protection Agency (EPA) as a tool for use in the Superfund program, which is responsible for remediating contaminated sites. The DRASTIC index represents factors which are used to evaluate groundwater vulnerability. These factors have scores assigned based on the characteristics of the site, and the scores are combined to produce a single index value that mirrors the comprehensive vulnerability of the groundwater at a specific site.

The DRASTIC index is typically used to prioritise sites for further investigation or remediation based on their relative vulnerability to contamination. It is an extensively employed tool for assessing groundwater vulnerability, and it has been applied in a variety of settings around the world – Table 1 (Engel *et al.*, 1996).

In the FAHP method, the groundwater vulnerability is decomposed into a hierarchy of criteria, with each criterion being evaluated in terms of its relative importance compared to the other criteria. The criteria can include factors such as geology, land use, and activities in the area, and the presence of potential contaminants. Once the criteria have been identified and their relative importance established, the FAHP method can be used to evaluate alternative courses of action or to rank different areas in terms of their groundwater vulnerability. This can be useful in identifying areas that may be at higher risk of groundwater contamination or depletion and in developing strategies to protect and manage these valuable resources (Al-Qudah and Al-Tarawneh *et al.*, 2013; Tiwari and Tiwari, 2016).

The fuzzy analytic hierarchy process (FAHP), initially introduced by Saaty (1980), is a framework for comparative standard that offers a valuable approach for modelling complex problems and incorporating subjective judgments in decision-making processes involving individuals or groups (Tan *et al.*, 2013). It enables to analyse and support decisions involving multiple sometimes competing objectives. This method is commonly employed to find out the appropriateness of a limited set of alternatives in relation to an overarching goal (Wang *et al.*, 2009). By ranking the importance and suitability of specific criteria, weights associated with the criteria can be determined (Sener *et al.*, 2009). The decision-making process in the FAHP is formulated as a hierarchical structure. Pairwise comparisons are used within the FAHP framework to estimate relative priority of criteria at each level of the hierarchy. While the FAHP aims to capture expert knowledge through perception or preference, it falls short of fully reflecting human thoughts using crisp numbers alone, as it relies on interval values. To address this limitation, the fuzzy FAHP method is applied, in particular to hierarchical fuzzy multi-criteria decision-making problems, where human judgment is better represented through fuzzy sets (Lee *et al.*, 2013).

The fuzzy analytic hierarchy process comprises a comprehensive and flexible method for evaluating and prioritising various factors and criteria related to water resources. By applying the FAHP in the Wadi AlHasa catchment, decision-makers and researchers can effectively assess and analyse the complex dynamics of water resources. The use of fuzzy logic enables to incorporate uncertainty and subjective input, allowing for a more accurate representation of real-world conditions and considerations. By applying the FAHP, decision-makers can gain valuable insights into the most effective strategies for water allocation, conservation, and sustainable development in the Wadi AlHasa catchment. This approach provides a robust framework for assessing and managing water resources, ultimately contributing to the long-term sustainability and resilience of the region's water supply.

The DRASTIC index includes two main parts; the hydrogeological setting part, which describes geological and hydrological elements influence groundwater movement within the aquifer, and the mathematical design of comparative hydrogeological elements (Kim and Hamm, 1999). In the DRASTIC method, each element has its specific rank between 1 and 10 (the higher value, the higher pollution potential). This evaluation is then compared by a weighting factor ranging from 1 to 5. The analytic hierarchy process (FAHP) can be used for critical assessment and support decisions with numerous aims. Influences of particular criteria are established by ordering their value and suitability; decision-making process is exposed as the FAHP method. The flowchart presented in Figure 2 shows how the GIS was combined with strengthening groundwater vulnerability maps using DRASTIC parameters (Navulur and Engel, 1997; Pathak *et al.*, 2009). The DRASTIC index (*DI*) has been defined in previous studies using Equation (3) (Fortin, Thomson and Edwards, 1997; Fritch *et al.*, 2000):

$$DI = DrDw + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw \tag{3}$$

where: each parameter defines the hydrological setting within the basin.

Table 1. DRASTIC index method for assessing groundwater vulnerability with fuzzy analytic hierarchy process (FAHP) method

Parameter	Range	DRASTIC relative weighting	FAHP rate	FAHP weight	Total weight
Depth to water (m) (*D*)	0–10	5	0.33	0.27053	0.089794
	10–20		0.29		0.076944
	20–30		0.25		0.066572
	30–40		0.11		0.028168
	>40		0.03		0.009106
Recharge ($m \cdot y^{-1}$) (*R*)	0.01–0.05	4	0.15	0.14931	0.023071
	0.05–0.1		0.23		0.033901
	0.1–0.18		0.29		0.043627
	0.18–0.25		0.33		0.048751
Aquifer medium (A)	massive shale	3	0.28	0.06508	0.018222
	metamorphic/igneous		0.25		0.01627
	massive sandstone		0.2		0.013016
	massive limestone		15		0.9762
	sand and gravel		0.1		0.006508
	basalt		0.4		0.026032
Soil media (S)	absent	2	0.26	0.00125	0.00033
	sand gravel		0.24		0.0003
	gravey sand		0.2		0.00025
	sandy clay		0.17		0.000213
	clay		0.13		0.000163
Topography (%) (T)	0–2	1	0.3	0.04451	0.013353
	2–6		0.22		0.009792
	6–12		0.18		0.008012
	12–20		0.17		0.007567
	>20		0.14		0.006231
Impact of vadose zone (I)	metamorphic	5	0.04	0.37715	0.015086
	ophiolic		0.09		0.033944
	volcanic		0.14		0.052801
	clay and sandstone		0.2		0.07543
	limestone		0.24		0.090516
	sand and gravel		0.28		0.105602
Hydraulic conductivity (*C*)	$<10^{-7}$	3	0.12	0.09216	0.011059
	10^{-6}–10^{-7}		0.18		0.016589
	10^{-5}–10^{-6}		0.21		0.019354
	10^{-4}–10^{-5}		0.24		0.022118
	10^{-3}–10^{-4}		0.26		0.023962

Source: own elaboration based on: Aller *et al.* (1987) and Şener and Şener (2015).

Equation (3) gives the DRASTIC index a hint of pollution risk to the aquifer in question. Impacts of various environmental conditions on groundwater vulnerability have also been summarised by Piscopo (2001).

Spatial characteristics (geology, water table, recharge, soil form) of the aquifer at Wadi AlHasa were gathered from several articles and reports, and then exported into ArcGIS 10.7. Next, the DRASTIC index equation was applied to produce a map with several vulnerability categories.

Before introduced into the aquifer, surface water is treated and filtered during the recharge process. This helps to remove contaminants and improve the overall quality of water stored in

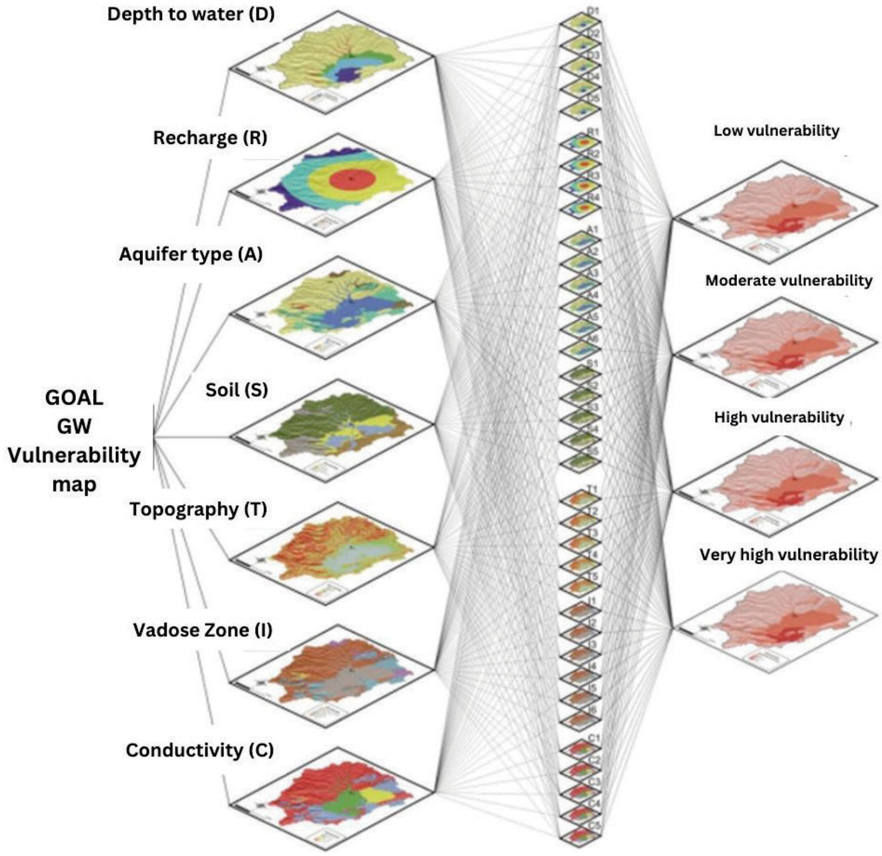

Fig. 2. Methodology to develop the groundwater contamination potential map using DRASTIC and fuzzy pattern recognition models in the framework of GIS; *D* = depth to groundwater, *R* = recharge rate, A = aquifer, S = soil, T = topography, I = vadose zone's impact, *C* = aquifer's hydraulic conductivity; source: own elaboration based on: Pathak *et al.* (2009) and Şener and Şener (2015).

the aquifer. Overall, the MAR offers a valuable solution for sustainable water management, providing resilience against drought, reducing reliance on surface water sources, and improving water quality in aquifers. By implementing MAR projects, communities and decision-makers can take proactive measures to secure water resources for the future. The implementation of MAR projects can provide significant benefits in terms of protecting the quality of groundwater resources used for drinking and other purposes. The final MAR map is derived from the integration and analysis of these thematic layers, as illustrated in Table 2. The development of such detailed MAR potential maps facilitates informed decision-making and enables water resource management to be carried out in a sustainable and responsible manner. By identifying areas with high MAR potential, stakeholders can prioritise and implement MAR projects effectively, contributing to the long-term availability and security of water resources.

These factors include (1) hydrogeological pattern, which examines the presence of rechargeable groundwater zones, (2) slope analysis, which is a necessary factor because topography stands out as one of the critical factors in succeeding recharge, (3) distribution of built up and urban areas which is an additional element that needs to be considered during the processing of MAR projects; these areas are excluded from the MAR project maps, and (4) availability of water resources within the target area which are to be obtained and applied for the recharge. Outcropped aquifers are rated as principal aquifers. Aquitards, the impermeable rock formations, should be excluded from MAR maps as they act as unfiltered areas. It should be noted that the MAR is only possible along aquifer outcrops.

Table 2. Combinations of classified slopes, hydrogeological classes and potential zones

MAR parameter	Proximity to water sources	MAR potential
Aquifer and slope <5%	no	high
	yes	very high
Aquifer and slope >5%	no	medium
	yes	high
Enhanced aquifer and slope <5%	no	very high
	yes	excellent
Enhanced aquifer and slope >5%	no	medium
Aquitard and slope <5%	no	low
Aquitard and slope >5%	no	low

Source: Rapp (2008), modified.

The application of the Rapp method (2008) shows that the highest potent slope for the MAR is ranging between 0% and 5%, below which a usual infiltration method can be applied with no increase for runoff. The study area was divided into two slope classes: 0–5%, which reflects a suitable class for the MAR model, and >5%, which reflects what is unsuitable for the MAR model. A map of urban areas was developed to resolve the issue of the thematic urban layer, with a linear buffer zone of 250 m set nearby urban zones. The urban areas are said to be non-preferable for aquifer recharge. Urbanisation can have a number of effects on the managed aquifer recharge (MAR), both positive and negative. Some of the potential effects of urbanisation on the MAR include increased demand for water; as urbanisation typically results in larger need for water, it can put pressure on surface water and groundwater resources. This can be particularly challenging in areas where water supply is limited or over-allocated. Additionally, urbanisation changes the land use, which often involves the conversion of natural land cover (e.g. forests or grasslands) to urban land (e.g. buildings, roads, and parking lots). This can alter the natural hydrological cycle and reduce the amount of recharge. Finally, it increases the risk of contamination due to the presence of more people and activities, such as industry and commerce, which can introduce pollutants into the environment. Thus, urbanisation must be taken into consideration through MAR projects to maximise the importance of such projects.

According to Gale (ed.) (2005), available water sources may include streams, wadis, reclaimed water, or constructed dams. Drainage systems can be used to collect surface water, such as storm water or irrigation water, and direct it to areas where it can be used to recharge aquifers. Wadis can also be used as channels to convey surface water to areas where it can be used for the MAR. In some cases, drainage systems and wadis may be modified or constructed specifically for MAR purposes. For example, drainage systems might be designed to maximise the amount of water that is collected and directed to recharge areas, or wadis might be lined with materials that help to filter out contaminants and improve the quality of water before it is introduced into the aquifer. Drainage systems and wadis can be particularly advantageous in regions where surface water is limited and the availability of groundwater is critical for maintaining economic and social stability. The managed aquifer recharge that uses drainage systems and wadis can help to augment groundwater supplies and reduce the demand on surface water sources. This can improve water sustainability.

Maps for these components within the target area were built, with a 5-km buffer zone around water bodies. A model of the drainage system in the area was developed with a buffer of 250 m.

The building of an interactive model to integrate both the groundwater vulnerability and the MAR project maps was provided. It can be a useful way to visualise and analyse the relationship between these two factors.

To build an interactive model of both groundwater vulnerability and MAR, gathering data on the groundwater vulnerability and MAR project maps are needed. This could include information on geology, land use, and potential contaminant sources in the area, as well as locations and characteristics of MAR projects. Next, it is necessary to develop a way to represent this data in a visual format to proof the relation between the two models. It might be created by digitising maps or diagrams that show locations and characteristics of MAR projects and levels of groundwater vulnerability. It is needed to develop an interactive component that allows users to explore the relationships between groundwater vulnerability and MAR projects. This could include features such as the ability to zoom in on specific areas, to toggle between different layers of data, or to view additional information about MAR projects and groundwater vulnerability. In general, an interactive model like this can be a valuable tool for comprehending the correlation between vulnerability and MAR projects, and for identifying areas where the MAR may be particularly effective in mitigating risks to groundwater resources.

The final map was built considering the higher vulnerability rates zones are excluded from MAR maps to prevent groundwater pollution. The development of this interactive component allows users to explore the relationships between groundwater vulnerability and MAR projects.

RESULTS AND DISCUSSION

The DEM for the basin shows that the topography is diverse; the land height ranges around 1150 m above sea level in the upper areas down to 400 m below sea level in the lower regions in the basin with more than 1500 m variation (Fig. 3a). Moreover, drainage channel intensity is developed northwest of the target basin while decreasing in the southwest, as shown in Figure 3b. The western tributaries of the Wadi AlHasa water network exhibit a tree drainage pattern, whereas the eastern streams demonstrate a central drainage pattern. The characteristics of the water network directly influence the magnitude and volume of stream floods in Wadi AlHasa following rainfall events. Among these properties, drainage mass, stream rate, bifurcation degree, and stream order play significant roles. Subdividing the areas with steep and rugged topography in the study area helped to determine six geomorphological forms according to the basin's geomorphological settings, as shown in Figure 4. The impact of surface relief is revealed in an escalation of the intensity of flash floods by amplifying the velocity of water flows in the tributaries to reach the significant wadi. Consequently, it synchronises the occurrence of stream floods with the peak water flow in the valley. Surface relief, or the topography of the land surface, can have a significant impact on the intensity of flash floods.

Flash floods are sudden, short-lived events that can occur during heavy rain falls over a short period of time, typically less than six hours. They can cause significant damage to infrastructure, agriculture, and the environment, and they can pose a serious threat to human safety. In areas with high-relief topography, such as mountainous or hilly regions, surface relief can increase the intensity of flash floods by channelling water into narrow valleys or streams, which can lead to increased erosion and sedimentation. High-relief topography can also create conditions where flash floods are more likely to occur, as the steep slopes and narrow valleys create a "funnel" effect that concentrates the water flow. On the other hand, in low-relief topography areas, such as flat or gently sloping areas, surface relief may have less impact on the intensity of flash floods. In these areas, water is more likely to spread out and flow more evenly over the land surface, which can reduce the risk of erosion and sedimentation and result in less intense flash floods. The geomorphology of Wadi AlHasa is influenced by a variety of factors, including the region's climate, geology, and the processes that have shaped the landscape over time. The geology of the area is primarily composed of sedimentary rocks, including sandstone,

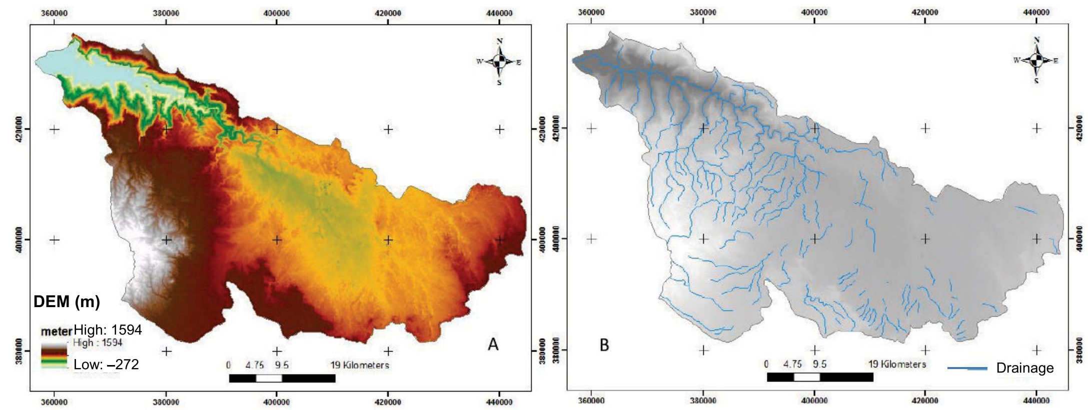

Fig. 3. Wadi AlHasa basin: A) digital elevation model (DEM) of study area, B) drainage system; source: own study

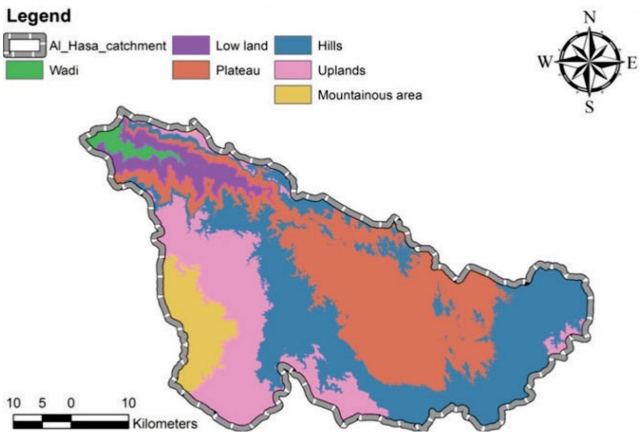

Fig. 4. Geomorphological units in study area; source: own study

shale, and limestone, which were formed over millions of years through a combination of sedimentation, compression, and heat and pressure. These rocks have been shaped and reshaped by a variety of geomorphic processes, including erosion, weathering, and tectonic activity. For the climate components model, rainfall and evaporation maps were interpolated using the Kriging method to generate the precipitation and evaporation pattern maps shown in Figure 5. Evaporation was determined according to the Penman method; interestingly, the evaporation records very high values due to high temperatures in summer. The values reach around 2800 mm·y^{-1} in some areas. Indeed, this is not the result of evaporation only because of limited water resources or soil water there. It is caused by the potential evaporation which means the amount of water evaporated depending on weather conditions. A thematic map for a runoff pattern was developed by estimating the runoff in the rainfall polygon according to the runoff coefficient, equal to 30%, estimated by GTZ 1977, accordingly. Runoff values range from around 7 mm·y^{-1} up to around 80 mm·y^{-1}; the resulted map is shown in Figure 5.

However, minimal recharge amounts will survive to seep from groundwater, especially in winter when the water is available in wadis and during rain events, also because of the decreasing temperature and reduced evaporation. These values are not very high as a result of low rainfall and significant evaporation (Fig. 6).

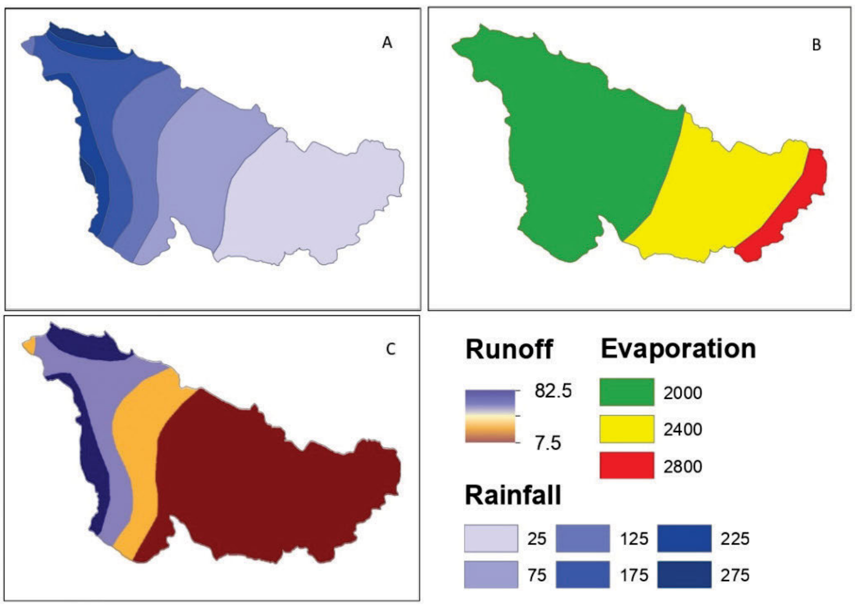

Fig. 5. Components of water balance in Wadi AlHasa: A) evaporation values according to Penman–Monteith method, B) rainfall pattern map, C) runoff values; source: own study, all records are in mm·y^{-1}

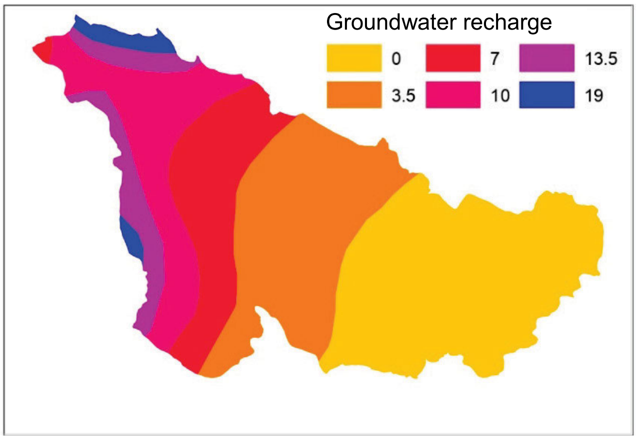

Fig. 6. Recharge distribution map (unit in mm·y^{-1}); source: own study

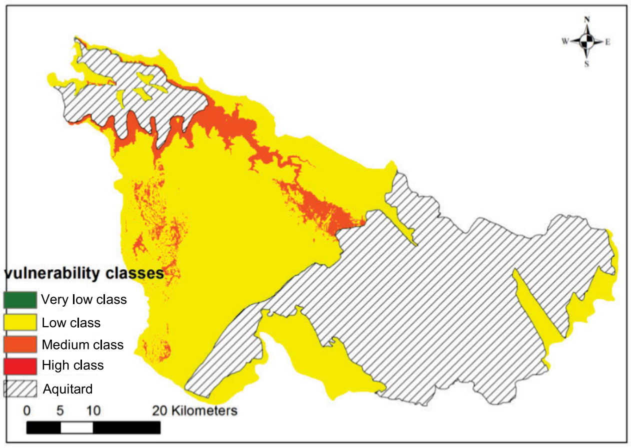

Fig. 7. Groundwater vulnerability index map for different upper aquifers within the target area; source: own study

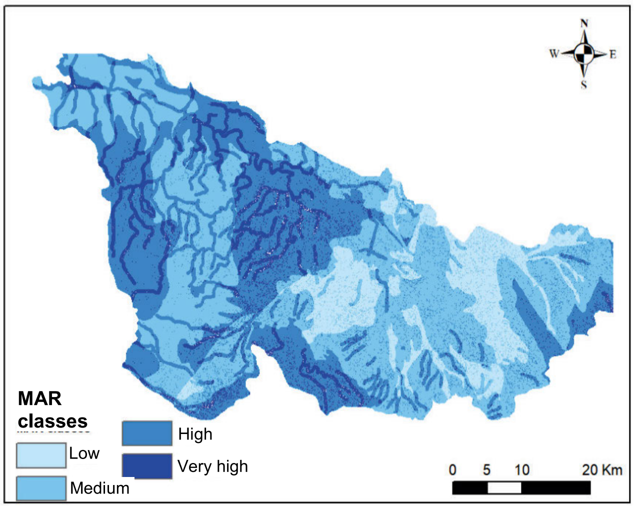

Fig. 8. Managed aquifer recharge (MAR) model map for different upper aquifers in Wadi Al Hasa; source: own study

A correlation of geomorphological units is shown in Figure 4, a groundwater recharge units map is shown in Figure 6; the figure shows that the highest recharge takes place in the mountainous areas. It is usually because the area receives the highest amounts of rainfall. Additionally, there is a high groundwater recharge in the plateau area due to limited occurrence of overland flow. In the north-western sections of the study area, the presence of an expanded drainage network leads to heightened flash flooding and reduced recharge of water resources. Flash flooding within the basin depends on its development and the discharged water flowing into channels. This observation signifies a state of balance between the volume of water and the channel capacity, any disruption to this equilibrium leads to stream flooding. The majority of stream floods in the basin occur as a result of rainstorm events, particularly in low sinks that impact the western highlands of the basin. These rainstorm events are characterised by intense, excessive rainfall and are concentrated within short timeframes. Precipitation rates might reach 50 mm in some areas during storms; thus, the outcome of these rainstorm events is contingent upon the severity of low depression that affects the region. There is often a correlation between geomorphological units and infiltration and groundwater recharge capacity, as the characteristics of the geomorphological units can influence the ability of ground to absorb water. For instance, geomorphological units consisting of porous and permeable rock types, like sandstone or limestone, tend to have a higher infiltration and recharge capacity compared to units with less porous and less permeable rock types, like shale or clay. Similarly, geomorphological units with gentle slopes generally exhibit higher infiltration and recharge capacity compared to units with steep slopes, as water is more likely to evenly flow over the surface and seep into the ground on gentle slopes rather than quickly runoff on steep slopes.

On the contrary, the DRASTIC vulnerability and FAHP DRASTIC maps for the study area revealed varying DRASTIC vulnerability index values, ranging from 0.08325 to 0.28409. Figure 7 presents the DRASTIC index map, which shows the target aquifers classified into four vulnerability categories: very low, low, medium, and high. The map further indicates that a significant portion of the area exhibits low to medium vulnerability. Utilising the MAR tool to assess groundwater potential within the aquifer, it is evident that the streams and wadis in the targeted area exhibit high potential for MAR projects (see Fig. 8). Conversely, extensive areas where aquitards are exposed should be considered as potential regions. The MAR classification ranges from low (55% of the total basin area) to medium (37% of the basin area), high (7% of the basin area), and very high (1% of the basin area). As illustrated in Figure 8, the outcropped aquifers with gentle slopes and close proximity to water sources display higher rates of important MAR classes. It can be concluded that topography plays a significant role in the MAR through infiltration, as the slope influences the duration of surface water retention on a specific area. An additional detailed analysis of this outcome presents the role of topography in influencing MAR results. Outcropped aquifers with gentle slopes and proximity to water sources show higher rates of practical MAR classes. This statement indicates that topographical features, in particular slope, play a vital role in the success of MAR initiatives. Gentle slopes enable enhanced infiltration, extending surface water retention over specific areas and consequently contributing to the effectiveness of MAR techniques.

Based on literature studies conducted in Jordan, it is evident that certain areas possess the potential for high recharge but also exhibit a high rate of groundwater vulnerability. This highlights the need to integrate both models to develop a comprehensive approach that allows for the identification of water resources without jeopardising the aquifer purity. Areas with high vulnerability, which can potentially contaminate groundwater, must be distinguished from a groundwater potentiality map and designated as high protection zones to prevent aquifer pollution. As a result, the final map presented in Figure 9 excludes regions with high vulnerability. The integration of groundwater potentiality and vulnerability maps in Figure 9 prompts reviews of applicable implications pertinent to the balancing of these elements. How can areas with high vulnerability be protected to prevent contamination of groundwater? What techniques can be applied to maximise the utilisation of areas with high groundwater possibility while undervaluing risks to water quality? Designing targeted protection zones based on vulnerability assessment could offer a proactive strategy for sustainable groundwater management. This refinement has led to changes in the percentage coverage of the MAR classes as follows: 18% of the area is now restricted, the low MAR class accounts for 31%, the moderate class for 28.2%, the high MAR class for 22.1%, and the very high class for 0.7% of the total basin area. The comprehensive analysis of the basin landscape, hydrological dynamics, and geological characteristics provides a more subtle interpretation of its complexity. Each segment opens routes for further research, showing the possibility of actionable insights that can contribute to sustainable water resource management strategies in Wadi AlHasa.

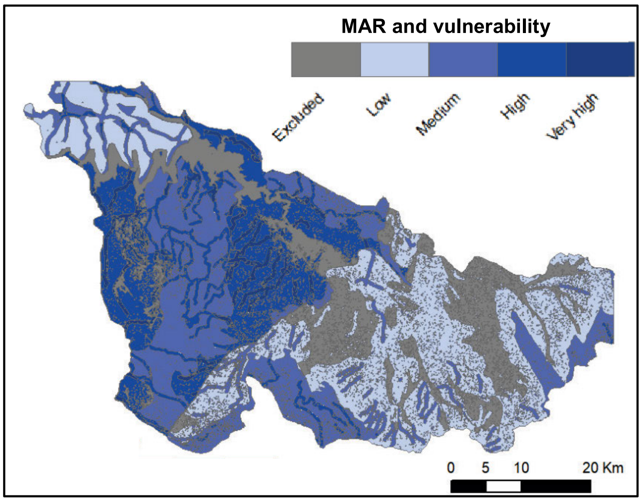

Fig. 9. Map produced by combining managed aquifer recharge (MAR) and DRASTIC model for Wadi AlHasa; source: own study

CONCLUSIONS

The conclusion based on the study underscores the pivotal role played by geomorphological units in influencing spatial distribution of flash floods, primarily through their impact on drainage density. Furthermore, it emphasises multifaceted factors that collectively shape floods within the Wadi AlHasa drainage system network, encompassing precipitation rates, basin properties, topography, valley slope, and channel morphology and capacity. Topography emerges as a central regulating factor not only in floods but also in groundwater dynamics, particularly with respect to rainfall distribution patterns. The topographic features significantly influence both groundwater recharge and vulnerability; the latter being further intertwined with underlying geomorphological units. In similar arid regions, highland and mountainous areas often exhibit shallow water tables, making them more susceptible to contamination compared to lower-lying areas with deeper water tables. The recognition of the intricate interplay between geomorphological units, infiltration, and groundwater recharge has profound impact on the effective water resource management. It is the cornerstone for identifying areas ripe with water infiltration and aquifer recharge, and thereby, progressing sustainable water resource utilisation. Moreover, the study underscores how geomorphological units, moulded by topography, decisively impact groundwater recharge. Highland and mountainous terrains, with their higher precipitation rates, tend to exhibit superior groundwater recharge rates compared to lowlands and wadi regions. While this study provides valuable insights into hydrological and hydrogeological systems and their intricate interactions within the study area, it also highlights the need for further research in similar arid to semi-arid regions. Groundwater vulnerability mapping emerges as a critical tool to ensure groundwater security and assessment. However, challenges persist, in particular in assigning ad hoc ratings and weights to various hydrogeological parameters necessary to assess vulnerability. The application of the fuzzy analytical hierarchy process (FAHP) offers a promising solution by integrating multiple functions and eliminating the need for manual assignment of weights to input variables. The study findings underscore the viability of the managed aquifer recharge (MAR) as a solution for countries struggling with limited water resources. The choice of MAR methods should be tailored to local conditions and project objectives, encompassing techniques, such as surface spreading, injection wells, and aquifer storage and recovery (ASR). When strategically employed alongside other water management strategies like water conservation and water recycling, these methods enhance water quality and provide an effective means for sustainable coverage of water demand. Importantly, it highlights the necessity to integrate MAR methods with groundwater vulnerability studies to protect water sources against contamination.

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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