Strategies for Sustainable Water Management: Hydrochemical Profiling and Protection Zone Design in Rania Basin, Iraq

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Abstract—**Groundwater in the Rania basin, Iraqi Kurdistan region, has been under intensive exploitation in the last two decades, where quantity and quality are both affected. Hence, any attempt to protect the aquifers has become an urgent need. Saruchawa, Qulai Rania, and Qulai Kanimaran are the three large springs, among dozens of others in the area, that are heavily relied on as the sole or main source of water supply. Hydrochemical analysis, the first and most practical step to evaluating the water quality, was carried out through 60 water samples collected from 13 springs and 17 wells in both dry and wet seasons (October 2018 and May 2019). Laboratory results show a high calcium bicarbonate concentration with weak acids' dominance. Protection zones are delineated for these springs using aquifer susceptibility to contamination and analysis of the recession part of the spring curves. The equivalent relationship between the protection factor (Fp) produced by the Epikarst, protective cover, infiltration condition, and Karst network development mapping method and the groundwater protection zone (S) is considered. Qulai Rania and Kanimaran Springs are mapped to be in S2 (a highly vulnerable area), whereas Saruchawa Spring is located in S1 (very highly vulnerable). Based on the second method results (recession curve analyses), all three selected springs fall under the (D-type) vulnerability category. As a result, the immediate protection zone was going to be surrounded by the inner protection zone, and both are enclosed within the outer protection zone, which covers the remainder of the catchment area.**

Index Terms—**Groundwater quality, Hydrochemical analysis, Rania basin, Vulnerability assessment, Water security.**

I. Introduction

Groundwater is mainly extracted through wells or by utilizing the discharge from springs – natural outlets for groundwater (U.S. Department of Agriculture Natural Resources Conservation Service, 2010). In mountainous regions, springs usually provide high-quality, gravity-fed water because there are fewer human impacts on the groundwater system than in urban or coastal areas (Filippini, et al., 2024). Groundwater from springs in northern Iraq in general, and in the Rania basin, in particular, has recently raised unprecedented concern among land users and related authorities. This has been caused by a severe drop in quantity and deterioration in quality which is mainly attributed to the rapid growth in urbanization and agricultural and industrial projects in the area in the last two decades. Despite the natural barriers provided by Earth's protective layers, recent decades have seen a significant increase in the risks facing groundwater, both in terms of its quality and quantity. This growing threat underscores the need for more rigorous protection and sustainable management of these critical water resources (Hamed Masoud, Dara Rebwar and Kirlas Marios, 2024). In urban regions, the presence of impermeable surfaces, modifications to natural streams, and built infrastructure can change how water infiltrates the ground, create new routes for subsurface water flow, and influence the quality of groundwater (Fryar, Currens, and Alvarez, 2023). It is well known that despite its significance as a vital source of water supply, groundwater may pose a significant health hazard if polluted due to difficulties in remediation. A balance between human activities such as urbanization, agriculture, and industry with groundwater protection could still be achieved if reasonable planning in land use is embraced (Meerkhan, et al., 2022). The physical and chemical properties of water must be investigated to decide on its suitability for different purposes as its not only quantity that is important but also its quality is important as well. The majority of past research on groundwater resilience has concentrated on analyzing trends in aquifer recharge, groundwater storage, hydraulic heads, and discharge. Only a small number of studies have examined the reality aspect of proposing protection strategies such as the delineation of source protection zones and aquifer features such as

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lithology, permeability, saturated thickness, transmissivity, and geometric properties of the fracture network (Filippini, et al., 2024; Zeydalinejad, 2023).

The Source Protection Zone is described as an area including surface and subsurface that surrounds a source of water, that is, a spring, or a wellfield through which pollutants may enter groundwater and reach the aquifer storage (US EPA, 2021).

According to Adams and Foster, 1992; Foster, Hirata, and Andreo, 2013, better ways of using the lands surrounding the source, coupled with delineating protection zones are vital to ensure the economic use of this important resource. Although many countries in Europe have already established three types of protection zones, a unified description on which all related authorities agreed has yet to be reached. The immediate zone, which occasionally includes swallow holes – natural depressions or sinkholes where surface water is drained into the ground, often disappearing into an underground river system – inside the catchment, is typically a region of 10 m wide surrounding a source (Doerfliger and Zwahlen, 1998). Zone (II) can also include certain places with favored infiltration and is regularly established on water passage time, 10–100 days depending on the member state (Doerfliger and Zwahlen, 1998). The remainder of the watershed or a minimum of 2 km or 400-day travel time restriction is bounded and referred to as the Outer Protection Zone (OPZ). (Doerfliger and Zwahlen, 1998; Al-Manmi and Saleh, 2019). The aim of this procedure, according to (Tarazi, 2009), is to protect potable water from pollution through the identification of specific zones that can be sources of potential harm around the water abstraction point.

Springhead/(zone I) immediate protection zone (IMPZ), (zone II) inner protection zone (IPZ), and (zone III) OPZ are subareas that accompany most groundwater protection schemes (Fig. 1). Some other programs add resource protection zone that covers the entire aquifer and often wider than the OPZ but not as wide as the whole catchment.

According to Al-Manmi and Saleh (2019), data availability and required precision are the two most influential factors when deciding on the extent of an area that needs protection from contamination and selecting the most suited method to delineate protection zones. Most of these standards and policies differ from one country to another. This difference is mirrored in zone numbers, the minimum required dimensions, and land-use regulations (Marín, et al., 2015). In places where karst aquifers are predominant, assessment models such as E epikarst, P protective cover, I infiltration, and K karst network (EPIK) (Doerfliger, et al., 1999; Hamdan, et al., 2016); COP (Vias, et al., 2006); VULK (Jeannin, et al., 2001); PI (Goldscheider, et al. 2010); and CPO + K (Marín, et al., 2015) have been tested to obtain a measurable vulnerability index of groundwater and assist in the allocation of protected areas. The most specific methods to identify protective zones and delineate the vulnerability around springs in karst aquifers are EPIK vulnerability mapping and spring recession curve analysis (Doerfliger, et al., 1999; Al-Manmi and Saleh, 2019). The hydrograph's recession curve is thought to convey the geometrical and hydraulic properties of aquifers and is typically more stable (Filippini, et al., 2024; Abirifard, et al., 2022; Segadelli, et al., 2021; Fiorillo, 2014). It is a combination of the discharge from individual blocks, which comes from water infiltration through diffusion, and the discharge from focused recharging through conduits (Rusjan, Lebar and Bezak, 2023; Kovacs and Perrochet, 2008).

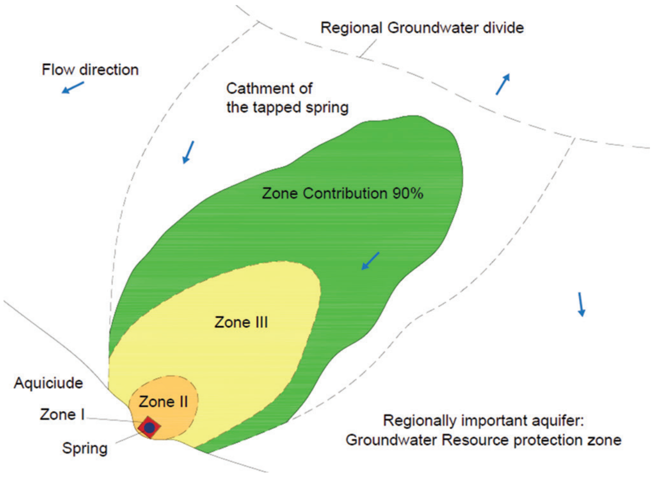

Fig. 1. Illustration of the protection areas around a spring (Goldscheider, 2005).

This paper aims to present a hydrochemical analysis of the basin's groundwater and delineate protection zones around three major springs of Saruchawa, Qulai Rania, and Kani Maran in the Rania basin using recession curve analysis and EPIK vulnerability mapping methods.

II. Materials and Methods

A. Study Area

The area of interest is located in Iraq's northeastern region of Kurdistan. It stretches from the northeastern part to the southwestern area in the Sulaimani province and is bounded by latitudes (36°05′15 ″, 36° 28′ 13″) and longitudes (44° 25′ 38 ″, 44° 58′ 51″). The area of the Rania basin covers something close to 1269.3 km^2. The town of Rania is 131 km away from Sulaimani city in the northeast direction (Fig. 2). Apart from Rania district, the basin extends to engulf Chwarqurrna, Hajiwawa, Betwata, and Hiran sub-districts as well as 100 s of villages scattered among the mountain valleys (Al-Manmi, 2008). In Table I below, the three major springs that are delineated in this study, together with their main characteristics, are tabulated:

A 35-year (1984–2019) average of climatological parameters taken from Dokan Meteorological Station at longitude (44°57'10") and latitude (35°57'15") was calculated. The rainy season spans from October to May. The maximum average monthly temperature is 34.1°C recorded in July, whereas the lowest monthly average is 6.2°C recorded in January. This considerable difference in temperature is one of the main characteristics of continental climate. Nearly, 53% of the yearly precipitation precipitates in the cold season (December to February) and about 30% in spring (March to May). Over the years (1984–2019), there

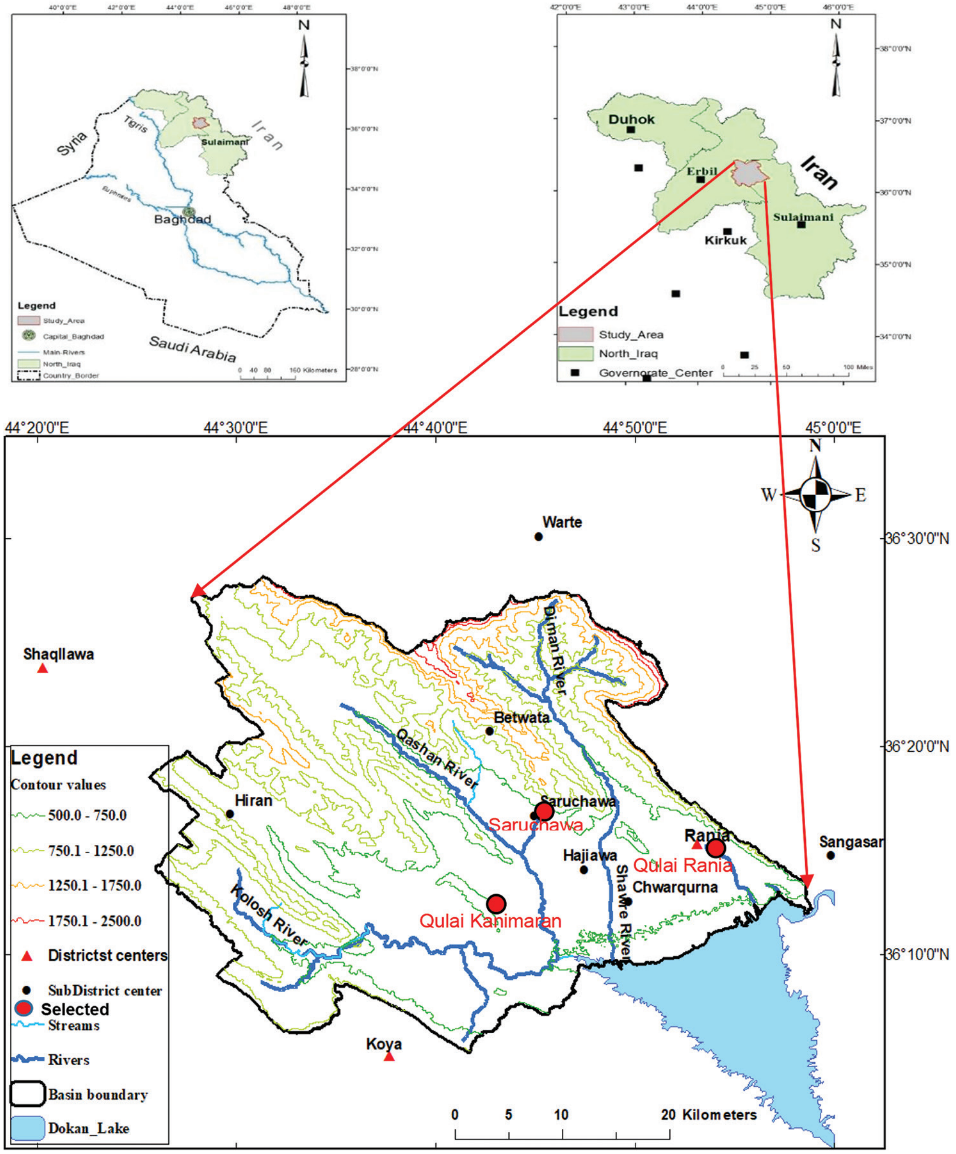

Fig. 2. Location of the selected springs and study area.

TABLE I
Information on the Three Springs Selected for Delineation

Spring name	Location	Coordinates	Elevation (m.a.s.l)	Yield (l/s)	Usage
Saruchawa Spring	Saruchawa sub-district	36°16'30"N, 44°45'18"E	582	6514	Largest spring in the basin
Qulai Rania Spring	Rania's inner district	36°15'20"N, 44°53'8"E	Not specified	780	Supplies two-thirds of Rania district's water
Kani Maran Spring	Kani Maran village	36°12'28"N, 44°43'34"E	541	513	Used primarily for agricultural purposes

has been an average of 682.5 mm of precipitation annually, whereas the maximum average monthly rainfall is 125.1 mm for December.

B. Geological Setting and Hydrogeology

The exposed geological units in the Rania basin, as surveyed by (Bolton, 1958; Bellen, et al., 1959; Buday, 1980; Buday and Jassim, 1987; and Jassim and Goff, 2006), are represented by 17 formations, starting from the Sarki formation of the lower Jurassic all the way up to Gercus formation of Middle Eocene, as well as recent deposits from Pleistocene, (Fig. 3a and b). In terms of water supply, quaternary deposits including floodplains, alluvial fans, and river terraces are considered the best units. The area of interest is situated in the lower Zab basin which itself is a part of the Dokan sub-basin.

According to Al-Manmi (2008) and as shown in (Fig. 4), there are four distinct aquifer systems; Quaternary, Early-Late Cretaceous, Late Cretaceous Limestone, and Jurassic systems, but the main is Quaternary. The direction of groundwater movement is from northwest to southeast.

The performed pumping tests of wells discharging from the studied basin showed that the transmissivity of the

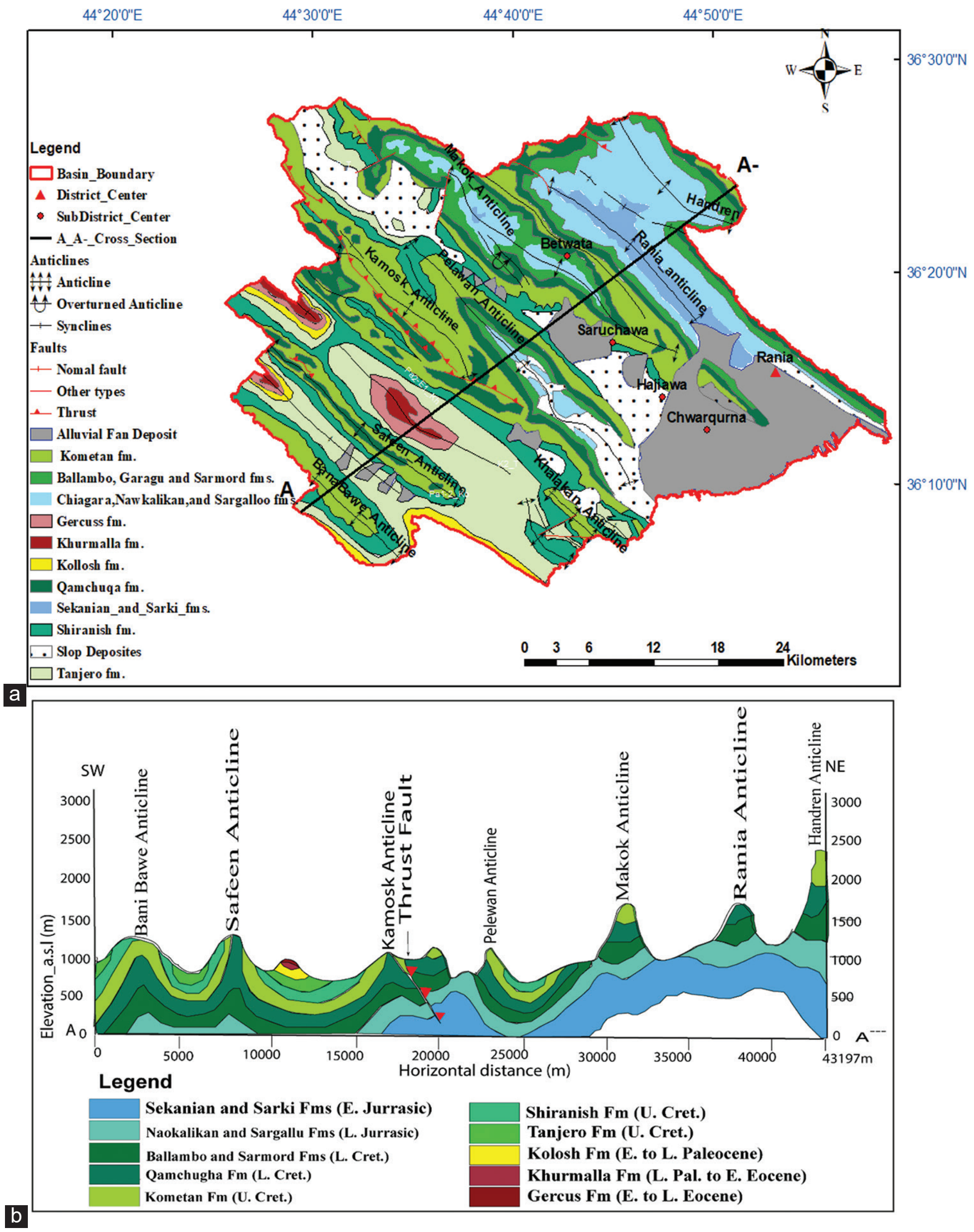

Fig. 3: (a) Rania basin's geology and (b) Geological cross section through line (A–A-), modified from (Sissakian, 1997).

aquifers ranges between 15 and 864 m^2/day, hydraulic conductivity ranges between 0.2 and 12.8 m/day, discharge of wells ranges between 3 and 1616 m^3/day and the static water level ranges between 5 and 60 m below ground surface. Recovery tests carried out in a neighboring area show a very high transmissivity value of 6–9 × 10^{-2} m^2/s (Stevanovic and Markovic, 2004). Aquifer's names, lithology, and their geological ages are all tabulated in Table II.

C. Quality Analyses for Hydrochemical Profiling

In situ measurements of temperature, electrical conductivity, and pH in 17 wells and 13 springs were recorded by a waterproof CyberScan PC 300 Portable pH/Conductivity/TDS Meter after calibration (Fig. 5). Small polyethylene containers of 500 mL were used to collect 60 water samples from 30 water sources penetrating the main aquifers in October 2018 (dry season) and May 2019 (wet season). They were then transported in a container surrounded by ice packs at 4°C till reaching the laboratory for analyses.

Laboratory-based analyses were carried out in the Sulaimani Health Protection Directorate based on guidelines of the American Public Health Association (APHA, 2012). The reason for conducting two rounds of sampling was to detect seasonal variations. For each analysis, a charge balance was calculated to check for analytical error.

D. Thematic Maps and Software

Geographic information system (GIS) ArcMap 10.5 was used to digitize previously drawn geological maps and cross-sections and construct shape files for geological, hydrogeological, and soil maps required for EPIK parameters in the delineation of the protection zones. After completing

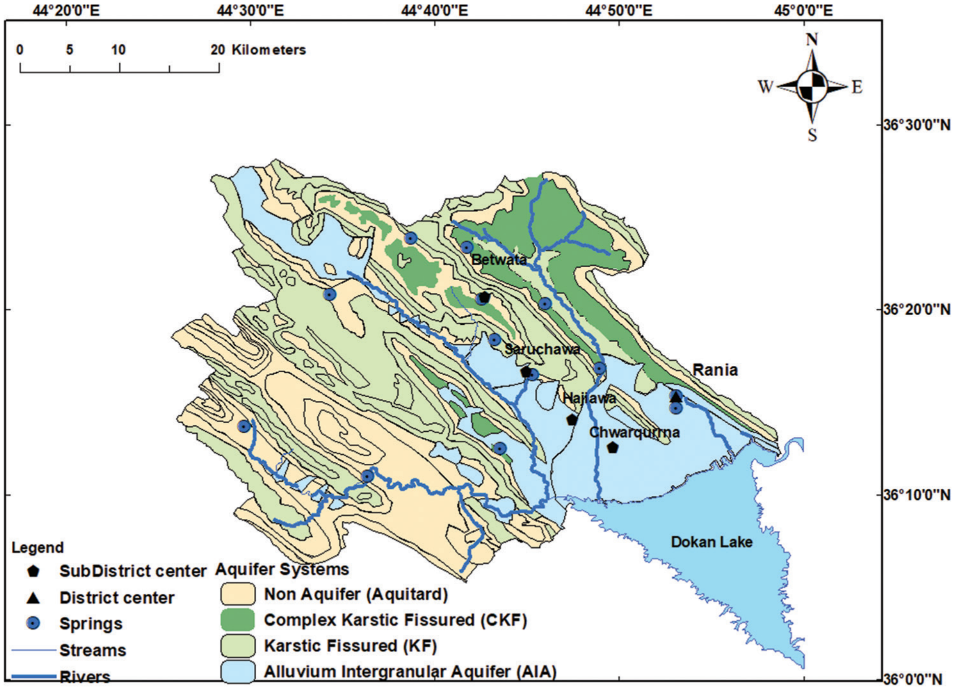

Fig. 4. Hydrogeological map, modified from (Al-Manmi, 2008).

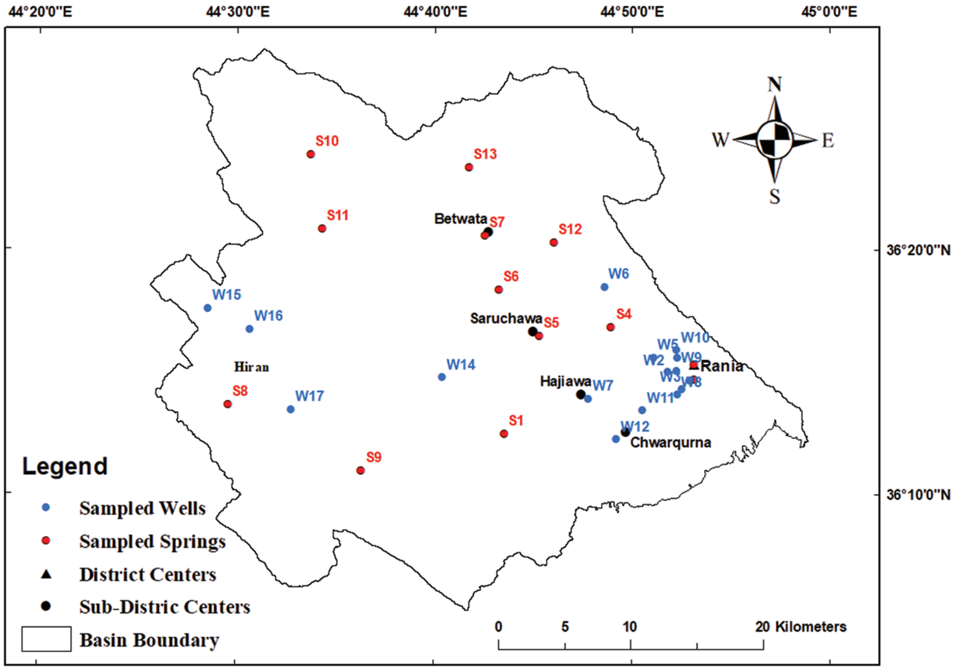

Fig. 5. Location map of wells and springs used for hydrochemical analyses.

TABLE II

Lithology, Age, and Thickness of the Main Aquifers in the Study Area, Modified from (Stevanovic and Markovic, 2004b; Aziz, 2002; Baban And Ali, 2002)

Aquifer names	Geological formations	Aquifer Types	Lithology	Av. Thickness (m)
Lower Jurassic aquifer	E. Jurassic: Sarki and Sekanian	Karstic Fissured	Limestone, cherty shale, and dark dolomite	300
Upper Jurassic aquifer	U. Jurassic: Chia gara, Naokalikan, Barsarin and Sargallu	Complex Karstic Fissured	Dolomite, limestone, marl, and organic matter-rich limestone	385
Bekhma Aquifer	E. to L. Creat. Bekhma, Kometan and Qamchuqa	Karstic Fissured	Limestone and dolomite	450
Quaternary Aquifer	Quaternary: Alluvial Fans and Slope Deposits	Intergranular	Gravel, sand, silt, and clay	100

the individual layers as shape files, (GIS) ArcMap 10.5 was also used to express the four EPIK variables as thematic layers before converting them into raster. Each factor was attributed weighting factor as per the EPIK equation, and a summation of the four layers yielded the final EPIK vulnerability map.

E. Conceptual Framework

Models that are commonly used in allocating protection zones for water wells are not necessarily adaptable in the delineation of spring protection zones, especially karst springs. This is attributed to the very little natural attenuation capacity karstic flowing water wells may have.

Required steps to ensure a secure and safe drinking water supply from a groundwater source are:

1. Identification of areas where pollutants can enter the aquifer and change the water quality
2. Prioritize such areas by assigning protective measures
3. Constant source monitoring and water treatment through filtration and disinfection.

These security procedures, if properly observed, will eventually ensure the provision of a safe-to-drink water supply (Goldscheider, 2005).

Hydrogeological techniques such as recession curve analysis and vulnerability mapping such as the EPIK model are the most widely used methods to identify features that control groundwater flow to springs and assist in delineating spring protection zones (Fig. 6).

Recession curve analysis

System characterization through time-dependent functions (recession function) has been continuously investigated since the early days of contemporary hydrology (Civita, 2008). Decomposing of the spring hydrograph reveals that the first steep part of the falling curve represents the contribution from the vadose zone, whereas the depletion curve represents the aquifer's input to the spring through its saturated zone. Furthermore, one of the functions of the recession curve is the pollutant's time of travel (TOT), with the infiltrated water to the spring. This (TOT) varies inversely with the natural attenuation factors and the recession curve's gradient, that is, the steeper the slope, the shorter the TOT and hence, the less attenuation capacity (Civita, 2008). To reach a recordable parameter to distinguish between different scenarios of hydrodynamic spring discharges and identify the pollutant's maximum displacement velocity in the spring-supplying aquifer, the spring's maximum discharge half-time (MDHT) is proposed and can be calculated through Eq. (1) (Civita, 2008).

$$MDHT = \frac{Qmax}{2} \cong t_i \qquad (1)$$

Where: Q_{max} is the maximum spring discharge in the year, that is, the days from the maximum annual discharge moment (Qmax) to the time when it is equal to Qmax/2. The depletion curves of the springs are plotted using their daily discharge rates on a nomogram to identify the corresponding range of flow velocity after computing MDHT (Fig. 7).

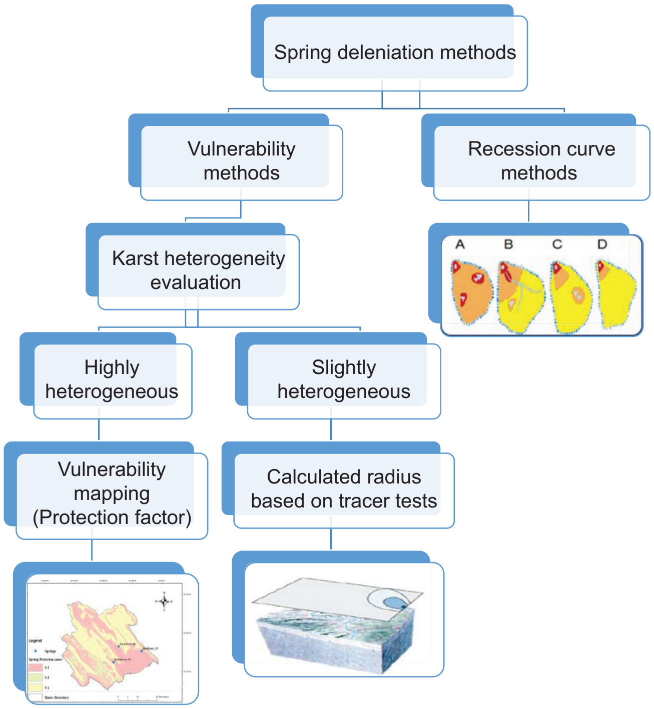

Fig. 6. Flowchart of common methods to delineate spring protection zones (Al-Manmi and Saleh, 2019).

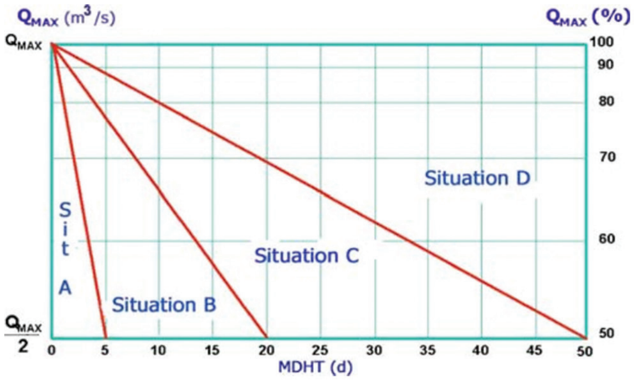

Fig. 7. A nomogram identifying basic A to D scenarios of pollution hazards of a karst spring (Civita and De Regibus, 1995; Civita, 2008).

Since the application of this model needs continuous daily readings of spring discharge to determine water's travel time in the saturated zone, the researcher resorted to the archived data of the selected springs. Recordings taken by FAO staff in the previous hydrologic years for Saruchawa, Qulai Rania, and Kani Maran springs were utilized in drawing hydrographs, analyzing recession cures, calculating MDHT, designating pollution hazards, and subsequently delineating protection zones for the interested springs.

The depletion curves of the springs are plotted using their daily discharge rates, and a nomogram is used to identify the corresponding range of flow velocity after computing MHDT. Delay time determines the MDHT in a way that the longer delay time produces a larger depletion and, therefore, a higher MDHT. However, a greater rate of discharge increases pollutant dilution capacity in contrast to smaller aquifers with a small outflow and a weaker dilution capacity. Therefore, a spring with a lower discharge should be considered more vulnerable. Thus, having considered all the aforementioned principles and pollution hazard scenarios, the designation standards for each protection zone around the springs are obtained (Table III).

Vulnerability mapping method (EPIK Model)

As this model is specially developed for karst aquifers (Awawdeh and Nawafleh, 2008), its application was also tried to delineate protection zones of the three springs of interest:

EPIK is an abbreviation composed of the first letters of epikarst (E), protective cover (P), infiltration conditions (I), and karst network development (K). Each of which is mapped and sub-sectioned into a series of divisions that are given a rating importance ranging from 1 to 4 and weighting values between 1 and 3 (Table IV).

According to SAEFL (2000), this model generates a color-coded map showing places relatively more susceptible to pollution from above the ground. The protection factor (Fp) is subsequently determined by adding the scores for each class of any particular parameter and multiplying by the allocated weight, as indicated in the equation below:

$$Fp = 3E+1P+3I+2K \qquad (2)$$

The Fp value could range between 9 and 34 and the greater the Fp value is, the better protection the area has, that is, the area is less vulnerable because the vulnerability rating and the protection factor are opposites. It can also be categorized into four susceptibility grades: Very high, high, moderate, and low (Table V).

TABLE III
IDENTIFIED SETTINGS BASED ON POLLUTION HAZARDS (CIVITA, 2008)

MDHT (d)	Scenario	Groundwater's velocity (m^3/day)
<5	A	>1000
5–20	B	≈100
20–50	C	≈10
>50	D	≈1

A. Epikarst (E)

Epikarst, according to Tripet, Doerfliger, and Zwahlen (1997), is defined as a zone of intensively karstified and highly permeable near the surface and under any consolidated soil if there is any. A map of Iraq's geology with a 1:250 000 scale which was compiled by Sissakian (1997) plus a geomorphological description with information on solution features in the studied basin also by Sissakian and Fouad (2014) were all used to surrogate for Epikarst as represented in (Table IV) and mapped in (Fig. 8a).

B. Protective cover (P)

This attribute is normally defined as upper unconsolidated or other non-karstic layers overlying the water-storing strata. To classify the protective cover in the studied basin and rate accordingly, detailed information on land cover and land

TABLE IV
APPRAISAL OF E, P, I, AND K FACTORS (DOERFLIGER AND ZWAHLEN, 1998)

Status	Code	Score		Description
Epikarst				
Karstic morphology observed (pertaining to epikarst)	E1	1		Caves, swallow holes, dolines, karren field, ruined-like relief, and cuestas.
Karstic morphology absent	E2	2		Intermediate zones in the orientation dolines, dry of valleys. Outcrops with medium fracturing
	E3	3		No karst morphological phenomena. A smaller number of fractures.
Protective Cover				
			A. Soil that is immediately resting on limestone or detrital deposits with extremely high hydraulic conductivity	B. Soil found on more than 20 cm of any unit of low hydraulic conductivity**
Protective cover absent	P1	1	0–20 cm of soil	-
	P2	2	20–100 cm of soil	20–100 cm of soil and low hydraulic conductivity formations
Protective cover important	P3	3	>1 m of soil	>1 m of soil and low hydraulic conductivity formations
Protective cover important	P4	4	-	>8 m of very low hydraulic conductivity formations or>6 m of very low hydraulic conductivity formations with>1 m of soil (point measurements necessary)
Infiltration Condition				
Concentrated infiltration Diffuse infiltration	I1	1	Temporary swallow hole – bands and beds of temporary or permanent rivers – parts of the tributary catchment having non-natural drainage	
	I2	2	Parts of a waterway catchment that are not artificially drained and where the slope is higher than 25% for meadows and pastures	
	I3	3	Regions of a waterway catchment that are not artificially drained and where the slope is lower than 10% for cultivated regions and lower than 25% for meadows and pastures. External regions to the watershed of a surface waterway: bases of slopes and steep slopes, where runoff water penetrates.	
	I4	4	Other parts of the watershed.	
Karst Development				
Well-built karstic network	K1	1	A well-built karstic system with decimeter to meter-sized conduits with little fill and well interlocked	
Unwell-developed karstic network	K2	2	Ill-developed karstic net with poorly interconnected drains of decimeter or minor size	
Mixed or fissured aquifer	K3	3	The existence of a spring developing through the porous territory only fissured aquifer.	

*Cases: Scree, lateral glacial moraine, **Cases: silts, clays

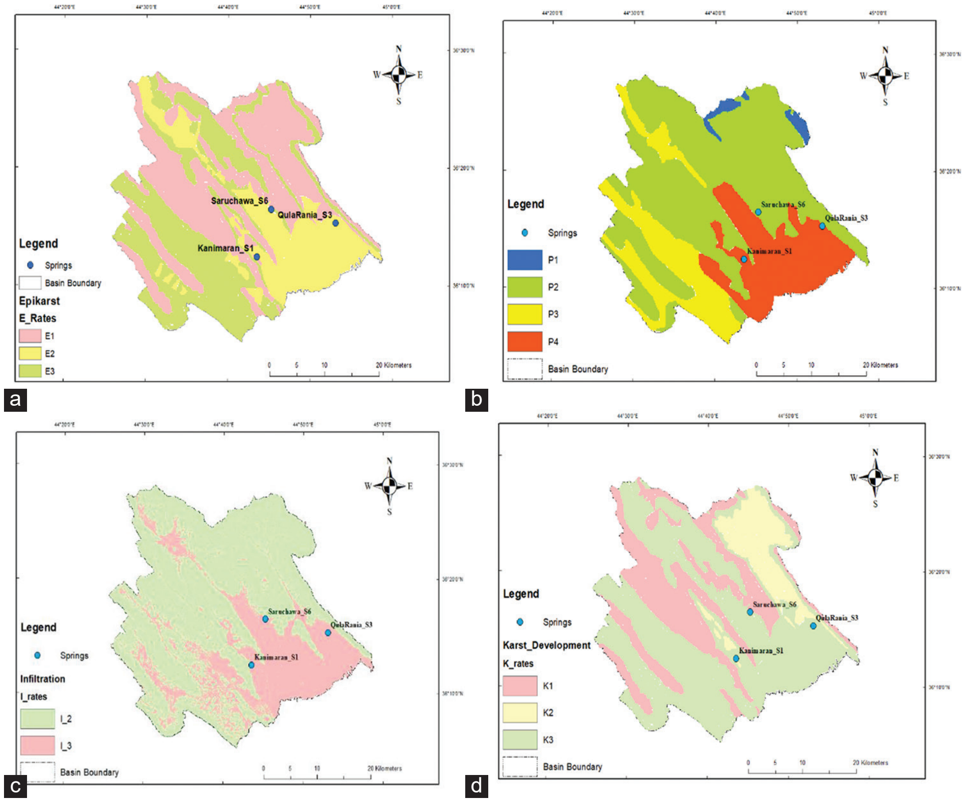

Fig. 8. (a) Epikarst rating map, (b) protective cover rating map, (c) infiltration rating map, (d) karst network rating map of the study area.

TABLE V
VULNERABILITY ZONES AND PROTECTION FACTOR

Protection factor (F)	Susceptibility grades
9–19	Very high
20–25	High
26–34	Moderate
More than 25 and in the presence of both P_4 and I3, 4	Low

use (LULC map), soil cover description coupled with soil classification, and hydraulic conductivity of different parts of the basin were all utilized (Fig. 8b).

C. Infiltration attribute (I)

The important aspect of this parameter is related to the type-specific effect of recharge in the karstic system. The studied basin, as shown in Fig. 8c, is divided into two zones of I2 and I3 only, since no perennial streams feeding swallow holes were reported in the basin.

D. Karst development attribute (K)

Ratings from (Table IV) were used to subdivide the studied basin into three categories ranging from K1 up to K3. K1 was assigned to areas where the well-developed karstic network is reported in outcrops of cretaceous formations such as Bekhme (locally Kometan) and Qamchuqa. K2 is given to Jurassic formation where a karstic network exists but is not well developed and K3 to the absence of karstic features in the quaternary alluvial fan and slope deposits and aquitards units such as Tanjero, Shiranish, and Gercus formations (Fig. 8d).

III. RESULTS AND DISCUSSION

A. Pollution Scenarios Based on Recession Curve Analysis

The protection area surrounding a spring is composed of three zones. Zone (I) or IMPZ, Zone (II) or IPZ, and Zone (III) or OPZ as shown in Fig. 9. Assigned distances and their restricted practices are represented in Table VI.

Recordings for the three selected springs of Saruchawa, Qulai Rania, and Qulai Kanimaran taken in the past by FAO staff have been used to draw hydrographs, analyze recession curves, calculate MHDT, designate pollution hazards, and subsequently delineate protection zones (Table VII and Fig. 10**)**. Thus, all of the three springs; Saruchawa, Qulai Rania, and Kanimaran fit the scenario of D-type. Therefore, The IPZ encloses IMPZ zones, whereas the OPZ includes the entire remaining catchment area.

B. Pollution level based on EPIK Protection Factor (Fp)

On completing the shape files for each parameter in ArcMap GIS 10.5, they were all converted to raster data with a 30 m grid. Each factor was assigned a weighting coefficient according to equation (2) and a summation of the four layers was obtained using the spatial analyst tool of the raster calculator. The final calculated protection factor produced by applying the EPIK model in the studied basin ranged from 12 to 28. Thus, the produced comprehensive EPIK map classified the vulnerability of the studied basin into moderate, high, and very high.

Areas categorized as having very high vulnerability (41.6%) are located in the northern parts of the studied basin

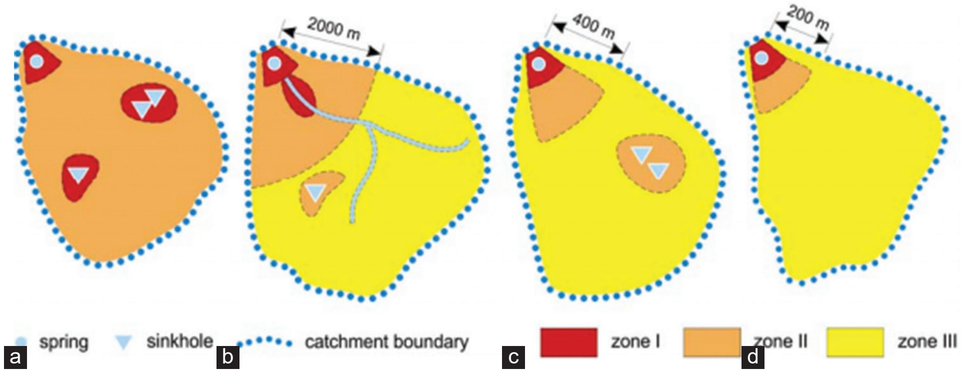

Fig. 9. (a-d) Pollution hazard scenarios and protection zoning (Civita, 2008).

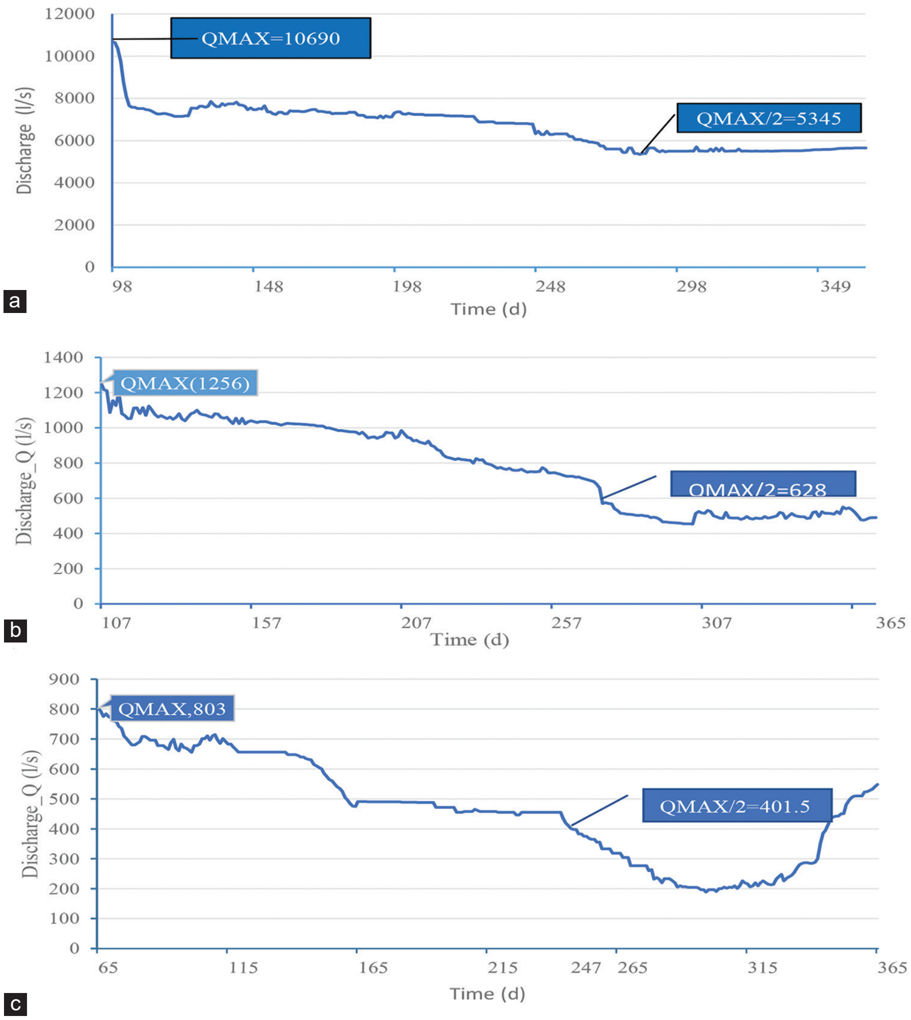

Fig. 10. Spring recession curve analyses (a – Saruchawa, b – Qulai Rania, c – Kanimaran).

TABLE VI
Enclosed areas and restricted practices for protection zones

Protection zones	Enclosed area (distance from the source) (m)	Remarks
Immediate (zone 1)	(10–40 m) upstream and (2–10 m) downstream	limited human activities except tree planting
Inner (zone 2)	- The whole catchment for (A and B) scenarios but decreased to (2 km) upstream for (B) scenario	In case of a thick protective cover or aquitards
	Upstream distance of (400–600 m) for C and (200–300 m) for D scenarios.	One zone higher if sinkholes exist!
Outer (zone 3)	Remaining of the whole catchment area	Restricted settlement and land use but safeguarding strategies are still needed.

where karstic features are not only present but also well developed, and the protective cover is absent or very thin, especially in the rocky outcrops of the mountainous regions.

It is also worth mentioning that Makok anticline, which is a karst system itself and is home to most of the major springs including Saruchawa spring, is situated in this vulnerability zone as represented in (Table VIII) and shown also in Fig. 11.

C. Final Spring Protection Zones Based on the EPIK Model

As represented in Table VIII, the protection factors obtained from the EPIK vulnerability model are used to designate specific spring protection zones. Fig. 12 illustrates that protection factors (Fp) ranging from 12 to 19 that may include dolines, swallow holes, and supplying watercourses are mostly categorized as S1, that is, least naturally protected

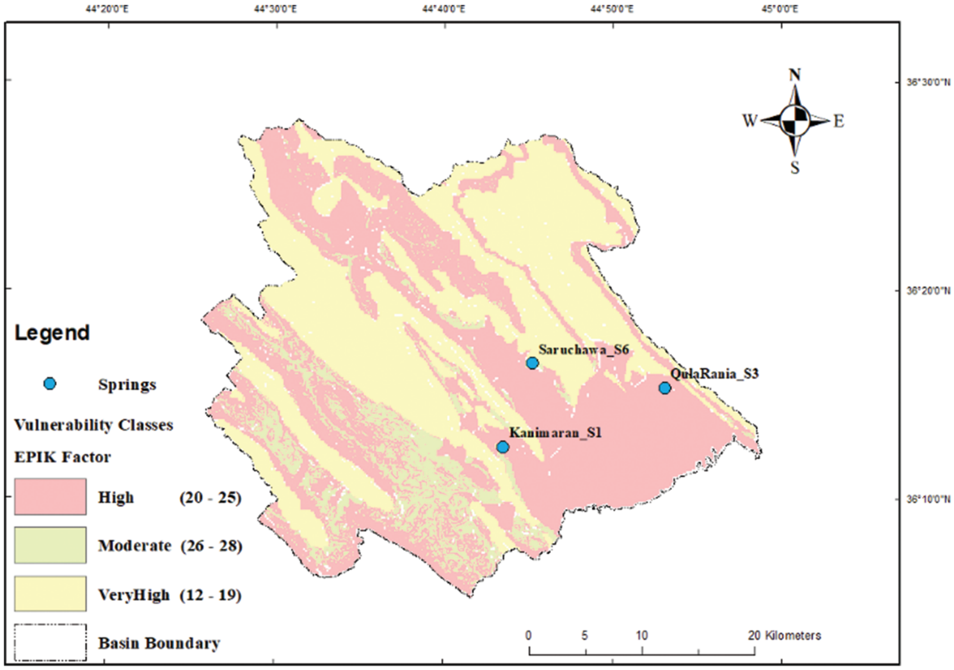

Fig. 11. EPIK vulnerability assessment map of the studied basin.

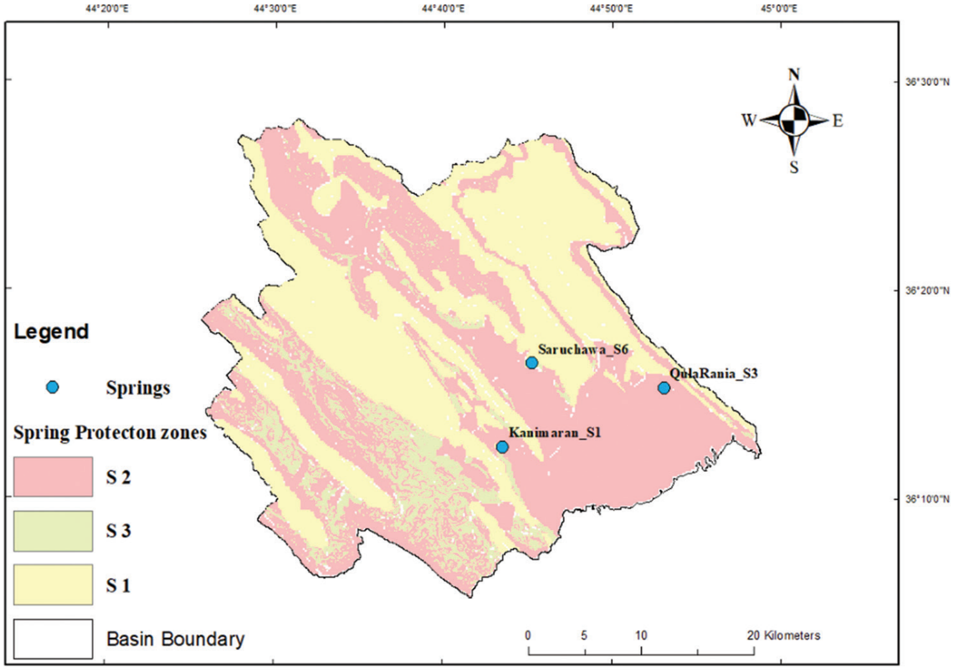

Fig. 12. Spring protection zones in the studied basin based on EPIK vulnerability.

TABLE VII
Discharge and MDHT assessment using recession curve analysis

Spring	Qmax (L/s)	Qmax/2 (L/s)	MDHT (day)	Scenario
Saruchawa	10690	5345	187	D
Qulai Rania	1256	628	166	D
Kanimaran	803	401.5	182	D

TABLE VIII
Area of vulnerability classes of the studied area using EPIK

Vulnerability	Protection factor (Fp)	Area (km^2)	Area (%)
Very high	12–19	528.52	41.63
High	20–25	621.25	48.94
Moderate	26–28	119.51	9.41

zone and has to be prioritized in terms of restricting certain actives such as extensive application of fertilizers and pesticides as well as dumping industrial refusals or untreated sewage water (SAEFL, 2000). Areas classed as having high vulnerability through the EPIK mapping model are given S2, whereas S3 is applied to those areas that have moderate vulnerability with a protection factor of 26–28.

The areas designed as zones of protection in the paper issued by the relevant authority in Switzerland adhere to the same constraints as the demarcated protection zones in EPIK (SAEFL, 2000). S2 and S3 include most of the drainage region for the springs, so certain operations such as installing gas stations, storing fuel, and infrastructural developments should be avoided. This is due to the limitations required by SAEFL (2000), connected with using each protection zone.

IV. Conclusions

This study presents a comprehensive hydrochemical analysis and vulnerability assessment for the Rania Basin's groundwater, focusing on three major springs: Saruchawa, Qulai Rania, and Kani Maran. The findings highlight the significant impact of intensive groundwater exploitation on both water quality and quantity, underscoring the urgent need for protective measures.

Hydrochemical analyses of 30 water sources, comprising 17 wells and 13 springs, reveal that the groundwater within the basin predominantly exhibits a calcium bicarbonate composition, characterized by alkalinity and a prevalence of weak acids. The physicochemical parameters measured across these samples align with the potability criteria established by the World Health Organization (WHO) and Iraqi standards, affirming the suitability of the basin's groundwater for consumption.

The delineation of protection zones using the EPIK vulnerability mapping method and recession curve analysis revealed varying levels of susceptibility across the springs, with Saruchawa being the most vulnerable. The results demonstrate the importance of implementing effective management strategies to safeguard these critical water resources. Areas categorized as having very high vulnerability (41.6%) of the entire basin are located in the northern parts of the studied basin (colored in yellow) where karstic features are not only present but also well developed and the protective cover is absent or very thin, especially in the rocky outcrops of the mountainous regions and around Makok anticline, which is a karst system itself and is home to most of the major springs including Saruchawa spring is least protected naturally and hence require prioritization for robust environmental planning in terms of restriction certain industrial and agricultural activities. Immediate and IPZs were recommended for each spring, with the aim of reducing contamination risks and ensuring sustainable water supply for the region.

Future efforts should focus on continuous monitoring, public awareness, and the integration of these findings into regional water management policies to mitigate potential threats to groundwater sustainability in the Rania Basin.

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