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RISK INTENSITY MAPPING OF COMPLEX AQUIFER SYSTEMS USING THE PHOSPHATE-DRASTIC MODEL: INSIGHTS FROM THE PENJWEEN BASIN, NE, IRAQ

Rebar Aziz Qaradaghy[1], Diary Ali Al-Manmi[2], and Dara Faeq Hamamin[3]

[1] Groundwater Directorate of Sulaymaniyah, Iraq. e-mail: rebar.qadir@univsul.edu.iq
[2] Diary Ali Mohammed Al-Manmi, Department of Petroleum and Energy Engineering, Technical College of Engineering, Sulaimani Polytechnic University, Sulaymaniyah, Iraq. e-mail: diary.amin@spu.edu.iq
[3] Department of Earth Sciences and Petroleum, College of Science, University of Sulaimani, Iraq. e-mail: dara.amin@univsul.edu.iq
***** *Corresponding author email: dara.amin@univsul.edu.iq*

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Abstract

Groundwater contamination from human activities is a significant concern for sustainable water resource management, particularly in Mediterranean climates such as the Penjween Basin (PB). Effective management requires comprehensive risk assessments, including hazard and vulnerability mapping. This study presents a novel approach by using phosphate (PO_4^{-3}) concentrations rather than nitrate (NO_3^-) to validate groundwater vulnerability assessments, providing a new perspective for contamination risk studies. Adhering to the European COST Action 620 guidelines, the methodology integrates hazard and vulnerability mapping with the PO_4^{-3}-DRASTIC model. Both standard and pesticide DRASTIC indices were employed to analyze vulnerability and determine the more reliable method for constructing a risk intensity map tailored to the region's complex aquifer system. The standard DRASTIC index categorized groundwater pollution vulnerability into four classes: Very low (23.2%), Low (47.7%), Moderate, and High. The pesticide DRASTIC index (88 - 207) identified five classes: Very low, Low, Moderate (39.9%), High (33.9%), and very high. Validation with phosphate concentrations from 40 groundwater sources (ranging from 0.01 to 4.86 mg/l, with 70% exceeding the Iraqi guideline of 0.4 mg/l) indicated that the pesticide DRASTIC model provided a more accurate representation of groundwater vulnerability in this region. The highest-risk areas, located in the southwestern region (Braim Awa Plain, Penjween Town) and along stream banks, are characterized by intergranular aquifers, intensive agricultural practices, and urban development. This study's novelty lies in the use of PO_4^{3-} as a validation parameter and the comparative analysis of standard and pesticide DRASTIC models to address complex hydrogeological conditions. The findings emphasize the importance of targeted management strategies, including restrictions on agrochemical use in high-vulnerability zones. Future research should focus on dynamic evaluation methods, improved monitoring systems, and

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sustainable agrochemical management to ensure long-term groundwater protection in regions with similar aquifer systems.

Keywords: Groundwater contamination; Risk assessment; Standard and Pesticide vulnerability; Mediterranean climate.

1. Introduction

Groundwater pollution is one of the most abundant problems worldwide and a crucial resource for over 1.5 billion people worldwide (Hudak, 2004). Groundwater typically has high quality in terms of purification and requires less treatment than surface water (Jamrah et al., 2008; Lavoie et al., 2015). The challenges of water quality and pollution of groundwater are critical issues of this century (Jakeman et al., 2016). In the last few decades, population growth and the intensification of agricultural and industrial activities have increased water demand and affected groundwater quality and quantity (Haque & Onodera, 2013). Addressing this requires conservation, efficient resource management, and innovative technologies to protect future water supplies (Balaji et al., 2023). The water quality and quantity are vital for agriculture and irrigation (Giordano, 2009; Siebert et al., 2010). A major risk linked to the use of agrochemicals is groundwater contamination, also to understand the nature of this contamination, it is essential to consider land use, soil composition, climate, and aquifer characteristics, along with the intrinsic properties of pesticides or fertilizers, such as their solubility (Adeoye et al., 2013; Pritchard et al., 2008). Over the past decades, groundwater has become a significant issue in the Iraqi Kurdistan Region (Hamamin, 2011; Qaradaghy, 2015; Hamamin et al., 2016). Numerous natural and human-induced factors contribute to the issue, including reduced annual rainfall, an increasing population, and the pollution of water resources (Al-Manmi, 2008). The study basin holds considerable hydrogeological and geological significance, yet its water resources are inadequately studied. Therefore, protecting against groundwater contamination threats is vital to maintain its quality. Studying groundwater quality in areas using agrochemicals such as fertilizers and pesticides is crucial to prevent future contamination (Adeoye, 2013). Phosphate (PO_4^{-3}), a vital component of fertilizers, is essential for crop growth and production, making it a significant element in agricultural chemicals used in modern farming (Pahalvi et al., 2021). After their application to crops, they are absorbed by soil and percolate through the soil after rain or floods, transmit the chemical with it, and are eventually leached to the underlying groundwater (Kulabako et al., 2007). The major sources of phosphate (PO_4^{-3}) include detergents from sewage discharge and waste from domestic and municipal landfills (Hamdan et al., 2018). Soil erosion in phosphate-rich areas further contributes to groundwater phosphate contamination (McDowell et al., 2004), and poorly maintained septic systems can also lead to phosphate leaching into groundwater (Ma, 2023). Protecting groundwater from pollution risks involves using a risk intensity map, a widely adopted method globally for assessing groundwater pollution risks (Hamamin et al., 2018). This tool is key for effective groundwater management. These assessments aid in identifying potential sources of harm and areas vulnerable to groundwater contamination, forming a critical foundation for decision-making in land planning and groundwater monitoring (Talozi & Hijazi, 2013). This approach entails creating three maps: Hazard, Vulnerability, and Risk Maps. In Iraq, Qaradaghy

(2015) pioneered the development of risk intensity maps using the DRASTIC method for the Sulaymaniyah sub-basin in the Kurdistan Region. After this, Mohammed et al. (2020) extended this methodology to encompass multiple water units within the Basra basin in northeastern Iraq. Similarly, Al-Gburi & Al-Tamimi, (2023) utilized the DRASTIC method to assess the Upper Al-Khasa sub-basin in Kirkuk province, Iraq.

The DRASTIC method evaluates groundwater vulnerability using seven parameters: (D) depth to water, (R) net recharge, (A) aquifer material, (S) soil material, (T) topography, (I) the impact of the vadose zone, and (C) hydraulic conductivity. Developed by the U.S. Environmental Protection Agency, it provides a standardized framework for assessing groundwater contamination risks (Aller et al., 1987; Evans & Myers, 1990). The vulnerability mapping technique provides a comprehensive overview of the geological and hydrogeological factors influencing the potential transfer of groundwater pollution within a specific area (Aller et al., 1987). The current work employs and compares both standard and pesticide DRASTIC indices to evaluate groundwater vulnerability, tailored to the complex aquifer system of the Penjween Basin. The DRASTIC standard scenario is more focused on municipal and industrial contamination, while the pesticide scenario modifies the standard framework to concentrate on pollution risks from agricultural chemicals. We emphasize the use of phosphate ($PO4^{3-}$) as a validation parameter instead of nitrate (NO3), which is commonly used in similar studies. This novel approach provides a new perspective on groundwater contamination assessment and highlights the specific risk of phosphate pollution, which is particularly relevant in agricultural regions. By correlating vulnerability classes with observed phosphate concentrations, the study validates the reliability of the vulnerability maps and offers a robust framework for assessing contamination risks in similar contexts.

2. Study Basin

The study basin is located 100 Km east of Sulaymaniyah City, northeast of Iraq. It covers an area of approximately 902 Km^2. The study basin, shaped like a crocodile's head, lies along a 125 Km border with Iran (Figure 1). As reported by the Sulaimani Statistical Directorate in 2021, the study area's population is approximately 54,221, with 55% residing in urban areas and 45% in rural areas. Based on information from the Groundwater Directorate of Sulaymaniyah , as stream water depletes and dries up, the residents of the study area depend entirely on groundwater during the summer to fulfill their needs, including those for livestock, agriculture, industry, and domestic use. Data from the Penjween Meteorological Station (2002-2022) indicate an average annual precipitation above 1000 mm, an average annual humidity of 53%, with an average annual temperature of 13.8°C. The study area experiences a Mediterranean climate with hot, dry summers and cold, snowy, and rainy winters (Al-Ansari, 2013; Mohammed, 2023). The basin's elevation ranges from 1055 m in the central and southwest to 2768 m (a.s.l) in the north and east, resulting in complex tectonic, topography and structures because it is located at the boundary between the Arabian and Eurasian plates (Jassim and Goff, 2006). The main geomorphological characteristics, including valleys (24% of the study area) such as Shalair and Darokhan, high mountain ranges like Kuta Rash, Barda Spi, and

Kani Shawaqat (29% occupy the study area), and hills and plains like Braim Awa Plain or Penjween Plain or Hill (46% of the study area). Additionally, agricultural lands occupy approximately 21% of the entire basin. The study basin is divided into two sub-basins based on topography and hydrology named Shalair and Qzlja, which are part of a huge transboundary basin called the lesser Zab basin (Mohammed, 2023). Shalair covers 638.8 Km^2, originating in the mountainous regions of the north and east, and flows through the Shalair Valley for 70 Km. Qzlja spans 263 Km^2, passing through the Braim Awa Plain for 29 Km. It begins with two tributaries: one in the mountainous areas of northwestern Iran (Mariwan Town) and the other in the Asen Kulen and Blkian Mountains. Shalair and Qzlja streams converge north of the village of Chamak to form the Siwayl River. Various rock units are exposed in the study basin (Table 1) and (Figure 2), and it encompasses igneous, metamorphic, and sedimentary rocks dating from the Late Jurassic to Holocene ages (Al-Qayim et al., 2012 & 2018; Ma'ala, 2008). Lithologically, the region comprises unconsolidated materials and solid rocks. Quaternary deposits along the valleys and streams, form alluvial fans and floodplains, creating thick mixtures of gravel, sand, silt, and clay. Water well profiles show sediment thickness ranges from 100 meters in the center to 5 meters at the edges, indicating a significant intergranular aquifer. Beneath these deposits, the solid geology includes complex igneous, metamorphic, and sedimentary rocks, forming the Complex Aquifer System (CAS) as classified by Stevanovic & Marković (2004b). Hydrogeologically, the basin contains two aquifer types: intergranular and fissure. The intergranular aquifer, composed of alluvial and flood deposits, covers approximately 22% of the basin and supplies substantial water resources for agriculture, and domestic use. The fissure aquifer, covering 78% of the basin, is predominant in areas with complex tectonics, topography, and structure. The productivity varies with the density of fractures and joints (Stevanovic & Markovic, 2003). According to groundwater level records, the depth to the water table in the basin ranges from 1.8 meters to 39.6 meters.

Table 1. Different rock units and aquifers in the study basin based on (Stevanovic & Markovic, 2003) and (Ma'ala, 2008).

Rock Units	Descriptions	Aquifer Types	Aquifer Dynamics	Area (%)
Flood and Alluvial Deposits	Pebble, Gravel, Sand, Silt, and Clay.	Intergranular (IA)	Medium to highly productive partly fractioned by impermeable clay layers, mostly unconfined.	21.7
Igneous Rocks	Plutonic and Kata Rash Groups	Fissured (FA)	Limited capacity and shallow aquifers.	10.98
Metamorphic Rocks	Gimo, Sirginil, Shalair Groups, and Darokhan limestone.	Fissured (FA)	Limited capacity and shallow aquifers with low-yield springs for discharge.	48.27
Sedimentary Rocks	Qulqula Radiolarian and U.Red Beds	Fissured (FA)	Low to medium capacity in limestone and volcanic rocks, interbedded with shale, marl, and siltstone.	18.65
Jurassic Rocks	Undifferentiated Jurassic Imbricates.	Karstic-Fissured (KFA)	Low productivity in dolomitic limestone. Shale layers are impermeable.	0.4

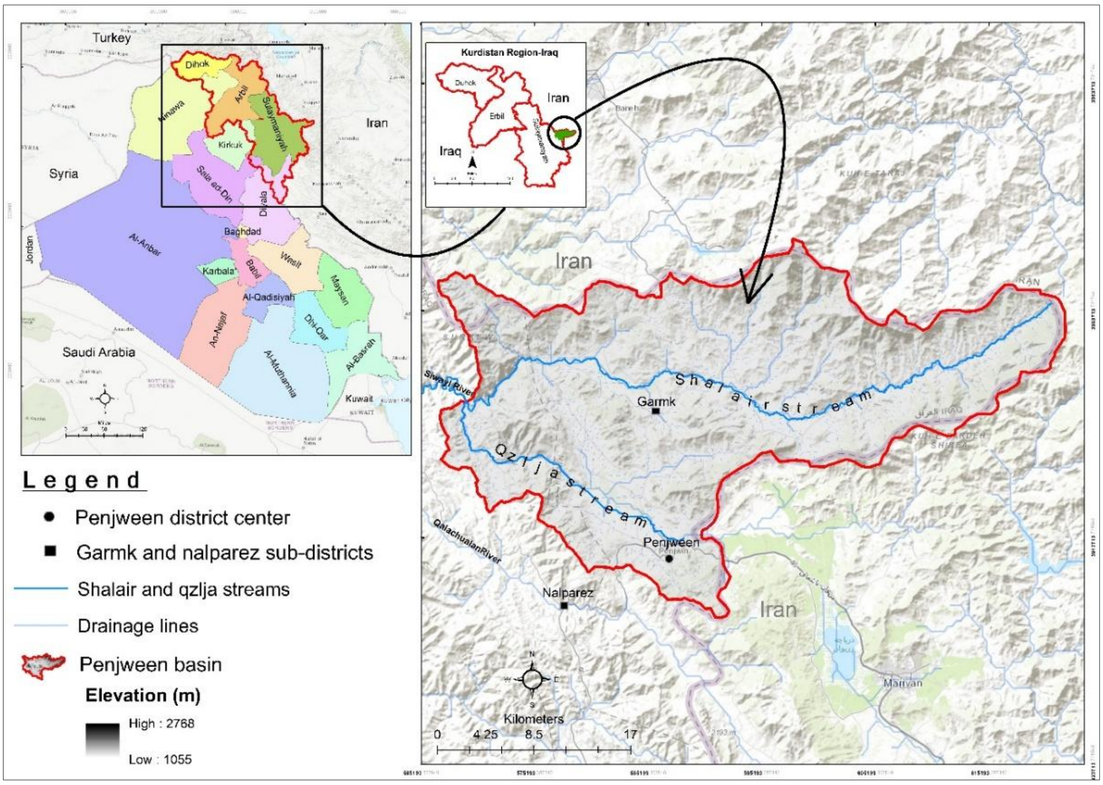

Figure1. Location map of the study basin.

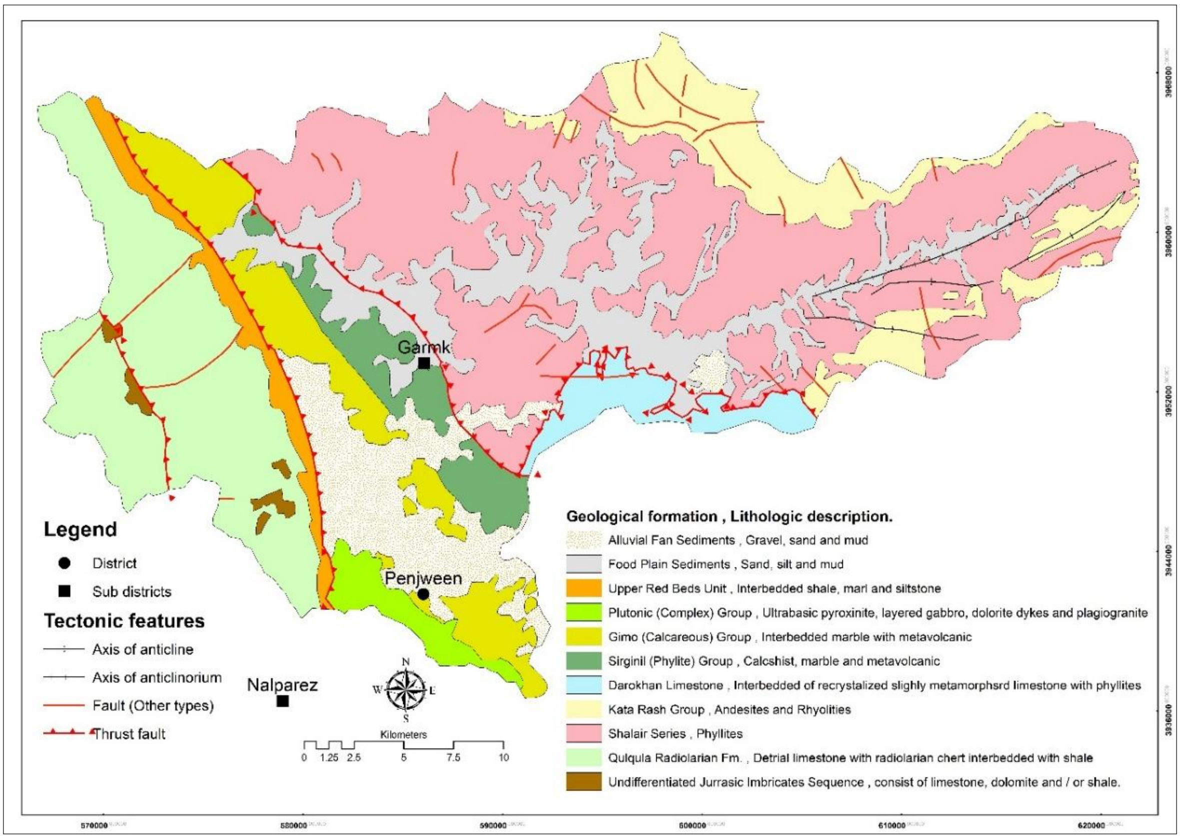

Figure 2. Geological map of the study basin modified from (Al-Qayim, 2012; Ma'ala, 2008).

3. Materials and Methods

The risk intensity map approach acknowledges that different hazard types and hydrogeological conditions result in varying vulnerabilities and levels of protection for underlying aquifers (Hötzl et al., 2004). The Pan-European strategy for hazard, vulnerability, and risk mapping, as defined by COST Action 620, employs an origin-pathway-target model for resource protection and source management (Zwahlen, 2003). The limitations of this methodology arise from the simplification of complex variables, issues with data availability and quality, dependence on current conditions, and the lack of dynamic evaluation (Zwahlen, 2003; Qaradaghy, 2015). In this study, the DRASTIC model is effectively tailored to the characteristics of the basin. The risk assessment methodology includes three main steps: data collection, mapping, and validation of DRASTIC vulnerability maps for phosphate (PO_4^{-3}) pollutants in pesticide scenarios. Figure (3) illustrates this methodological procedure.

3.1. Data Collection

The fieldwork, conducted from 2022 to 2023, involved comprehensive geological and hydrogeological studies for the area. Essential information on geology, hydrogeology, hydrology, geological maps, soil, and high-resolution DEM with 15 meters were collected. Profile and lithology column data were gathered from more than 100 wells provided by the Sulaimani Groundwater Directorate /GIS Unit. Land use and land cover data, including details of winter and summer crops, were obtained from Landsat-8 /OLI satellite imagery. Meteorological data (rainfall, snowfall, humidity, temperature, and sunshine) from the Penjween Meteorological Station were also collected for the periods between 2002-2022. To evaluate the aquifer characteristics, 18 pumping tests were conducted, and groundwater levels in 60 drilled wells were recorded. Groundwater samples for phosphate (PO_4^{-3}) analysis were collected from 40 groundwater sources, including 15 deep wells, 12 shallow wells, 6 hand-dug wells, and 7 springs. Several computer programs were used for this research: Excel for organizing collected information and data, ArcGIS v.10.8 for analyzing and creating maps, and AQTESOLV for analyzing pumping test data.

3.2. Mapping

3.2.1. Hazard Index (HI)

Based on the European COST Action 620 report by Zwahlen (2003), the hazard type in the study basin can be determined through the following steps: defining and inventorying hazards, specifying hazard data requirements, and applying weighting, ranking, and reduction factors to create unclassified and classified hazard maps. Table (2) shows the potential degree of harmfulness for various hazard types, assigned according to the resulting hazard index (Equation 1), the harmfulness of different hazards is expressed as the hazard index (**HI**), indicating the degree of harmfulness to groundwater. The weighting (**H**), ranking (**Q_n**), and reduction factors (**R_f**) are estimated based on the hazard's relative size and technical conditions.

$$HI = H \times Q_n \times R_f \quad (1)$$

Where H is the weighting value of each hazard, Q_n is the ranking factor (0.8 to 1.2), and R_f is the reduction factor (0 to 1).

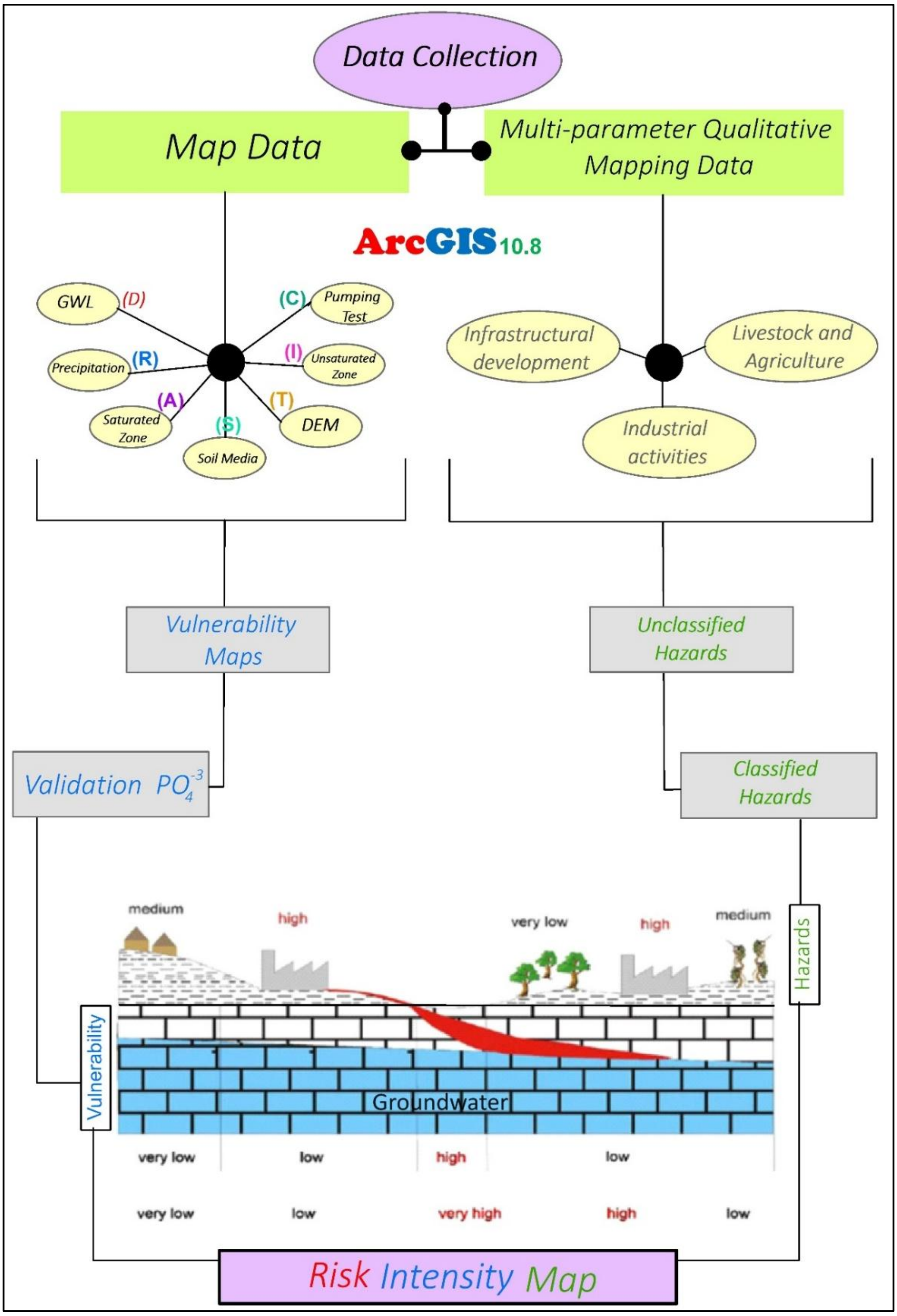

Figure 3. Flow chart of the methodology adopted.

Table 2. Weights and categories of different groundwater hazards in the study basin based on European COST Action 620 reported by (Zwahlen, 2003).

No.	Hazard types	Weighting values	Feature types
1	**Infrastructural development**		
1.1	*Wastewater*		
	Urbanization (leaking sewer pipes and sewer systems)	35	Polygon
	Urbanization without sewer systems	70	Polygon
1.2	*Fuels*		
	Storage tank, above-ground	50	Polygon
	Gasoline station	60	Polygon
1.3	*Transport and traffic*		
	Road, unsecured.	40	Line
	Road Hhaulier depot	35	Line
	Car parking area	35	Polygon
1.4	*Recreational facilities*		
	Tourist urbanization	30	Polygon
	Open sport stadium	25	Point
1.5	*Diverse hazards*		
	Graveyard	25	Polygon
	Transformer station	30	Point
2	**Industrial activities**		
2.1	*Excavation site*		
	Quarry	25	Point
3	**Livestock and Agriculture**		
3.1	*Livestock*		
	Factory farm	30	Polygon
3.2	*Agriculture*		
	Open silage (field)	25	Polygon
	Intensive agriculture area (with high demand for fertilizer and pesticides)	30	Polygon
	Allotment garden	15	Point
	Greenhouse	20	Point

3.2.2. DRASTIC Index (DI)

To generate an accurate DRASTIC vulnerability map, a comprehensive understanding of the geology and hydrogeology of the area is essential. The final vulnerability map is produced by integrating seven key hydrogeological and geological parameters. The DRASTIC map comes in two scenarios: one for industrial and municipal pollutants (standard) and another for agricultural pollutants (pesticides). The Standard and Pesticide DRASTIC model produces a numerical index dependent on the weights and ratings given to the eight model parameters. Parameters are weighted from 1 to 5 based on their relative contaminant susceptibility. Ratings from 1 to 10 are assigned to each parameter, with 1 indicating lower vulnerability to contamination and 10 indicating higher vulnerability as shown in Table (3). The equation for calculating the DRASTIC index of a mapping unit is as follows:

$$(\mathbf{DI}) = Dr*Dw + Rr*Rw + Ar*Aw + Sr*Sw + Tr*Tw + Ir*Iw + Cr*Cw \quad (2)$$

Where; **DI** is the DRASTIC index, and **r** is the rating value. **w** is the weight associated with each parameter.

Table 3. Ratings and weights of the DRASTIC parameters (Aller et al., 1987).

Parameters	Rating	Class interval	Standard Weights	Pesticide Weights
Depth to groundwater	1	More than 30	5	5
	2	30 - 23		
	3	23.1 - 19		
	4	19.1 - 15		
	5	15.1 - 12.5		
	6	12.51 - 10		
	7	10.1 - 7.5		
	8	7.51 - 4.5		
	9	4.51 - 1.5		
	10	Less than 1.5		
Net recharge (mm/year)	1	Less than 50	4	4
	3	50 - 100		
	5	100 - 140		
	6	140 – 180		
	7	180 - 215		
	8	215 - 250		
	9	More than 250		
Aquifer media	10 - 9	Karst limestone	3	3
	10 -2	Basalt		
	9 - 4	Sand and gravel		
	9 -4	Massive sandstone, massive limestone		
	9 - 5	Bedded sandstone, limestone, shale		
	6 -4	Glacial till		
	5 - 3	Weathered metamorphic/igneous		
	5 - 2	Metamorphic/igneous		
	3 - 1	Massive shale		
Soil media	1	Nonshrinking and non-aggregated clay	2	5
	2	Muck		
	3	Clay loam		
	4	Silty loam		
	5	Loam		
	6	Sandy loam		
	7	Shrinking and/or aggregated clay		
	8	Peat		
	9	Sand		
	10	Thin or Absent, Gravel		
Topography	10	0 – 2	1	3
	9	2 – 6		
	5	6 – 12		
	3	12 – 18		
	1	More than 18		
Impact of the vadose zone	10 – 8	Karst limestone	5	5
	10 – 2	Basalt		
	9 – 6	Sand and gravel		
	8 – 2	Metamorphic/ Igneous		
	8 – 4	Sandstone, Bedded limestone, sandstone, shale, sand and gravel		
	7 – 2	Limestone		
	5 – 2	Shale		
	6 – 2	Silt/ clay		
	1	Confining layer		
Hydraulic conductivity (m/day)	10	More than 80.0	3	2
	8	80.0 – 40.0		
	6	40.0 – 30.0		
	4	30.0 – 12.0		
	2	12.0 – 4.0		
	1	Less than 4.0		

3.2.3. Risk Intensity Index (RII)

The boundaries of the risk classes are determined by the limits of the hazard index and vulnerability factor (Table 4), making it straightforward to apply this method to vulnerability assessments. The calculation of the risk intensity index incorporates the effects of the hazard index (**HI**) and standard DRASTIC index (**DI**) using (Equation 3), as proposed by Zwahlen (2003) and Hötzl et al. (2004).

$$RII = 1/HI \, . \, \pi \qquad (3)$$

RII: Risk Intensity Index, HI: Hazard Index, VI or π: Index for DRASTIC vulnerability map.

Table 4. Risk intensity map classification.

π −Factor (DI)	Hazard Index	1/HI	$1/HI \, . \, \pi$	Risk class	Risk Level
< 100	0 - 24	>0.042	> 4.2	1	No or very low
100 - 125	>24 - 48	0.042 – 0.021	4.2 – 2.625	2	Low
126 - 150	>48 - 72	0.021 – 0.014	2.625 – 2.1	3	Moderate
151 - 200	>72 - 96	0.014 – 0.010	2.1 – 2	4	High
> 200	>96 - 120	<0.010	< 2	5	Very high

3.3. Validation of DRASTIC map

Most vulnerability maps undergo validation. Using unvalidated information can lead to erroneous conclusions and subjective risk assessments. To prevent this, parameter comparison testing and mapping validation alternatives are essential (Leal & Castillo, 2003). Here, phosphate (PO_4^{-3}) was used in this study to validate a standard and pesticide vulnerability map. Groundwater samples were collected from 40 groundwater sources. Well locations were overlaid on both scenario maps to investigate the relationship between groundwater vulnerability and PO_4^{-3} concentrations. The spatial joining of the two layers was achieved using the location operation in ArcGIS, allowing for the analysis of assigned data based on well positions.

4. Results and Discussion

The lack of effective water management plans, inappropriate land use practices, and improper use of agrochemicals exacerbate the situation. Additionally, there is a lack of awareness and support for farmers, leading to inadequate irrigation and drainage projects. Inappropriate solid waste disposal and the drilling of numerous unauthorized wells for public, industrial, and agricultural purposes further exacerbate the issue. The combined impact of these factors significantly strains the available water resources, posing a serious challenge to sustainable water management and environmental health. Without effective intervention, these issues are expected to increase in severity over time.

4.1. Hazard maps

4.1.1. Unclassified hazard map

For this study, hazards are divided into three major categories; urban hazards, Industrial hazards, and agricultural hazards. Hazard data is derived from satellite images, land use/ land cover (LU/LC) maps, and field surveys. These sources provide both spatial information and specific attributes necessary for analysis. This study identified seventeen types of hazards (point, line, and polygon), as shown in Table (2) and Figure (4a). Point hazards, like transformer stations, allotment gardens, greenhouses, open sports stadiums, storage tanks, gasoline stations, and quarries are concentrated around Penjween Town. Line hazards include road unsecured and road hauler depots, while polygon hazards cover areas such as open silage fields, urban areas with sewage issues, tourist areas, and intensive agriculture areas. The resolution of the unclassified hazard map can be problematic where multiple hazards coexist, leading to higher harmfulness classifications.

4.1.2. Classified hazard map

The classified hazard map indicates that most hazard indices fall within classes 1 and 2, with "no or very low" and "low" hazard levels being predominant (Figure 4b). It's important to note that even a detailed assessment only represents the current situation. The type or degree of hazards may change in the future due to infrastructural, industrial, and agricultural developments in the study basin. The vector model of unclassified hazards was converted into a raster format with a 15-meter cell size to create the classified hazard map. The final map was created and reclassified based on the range proposed by Zwahlen (2003). According to this map, the majority of the study area (79.5%) falls within the "no or very low" hazard level, while (20%) is classified as a low hazard level.

4.2. DRASTIC maps

4.2.1. Standard DRASTIC map

The standard DRASTIC Index values, integrating seven parameters, are classified as shown in Table (5) and Figure (5). The pollution vulnerability index, ranging from 64 to 176, is divided into Very Low, Low, Moderate, and High classes. The very low and low vulnerability classes cover most of the study area, 210 Km^2 (23.2%) and 431 Km^2 (47.7%) respectively, predominantly in the hills and mountains regions. They consist of fissured aquifers with igneous and metamorphic rocks. Moderate and High vulnerability areas are in Braim Awa Plain, Penjween Town, and near streams, consisting of intergranular aquifers including pebble, gravel, sand, and silt. These areas rated high in parameters such as (Net recharge, Aquifer media, Topography, and Hydraulic conductivity). Precisely, 15.7% of the area has a moderate vulnerability, while 13% has a high vulnerability to industrial-municipal pollutants or standard scenarios.

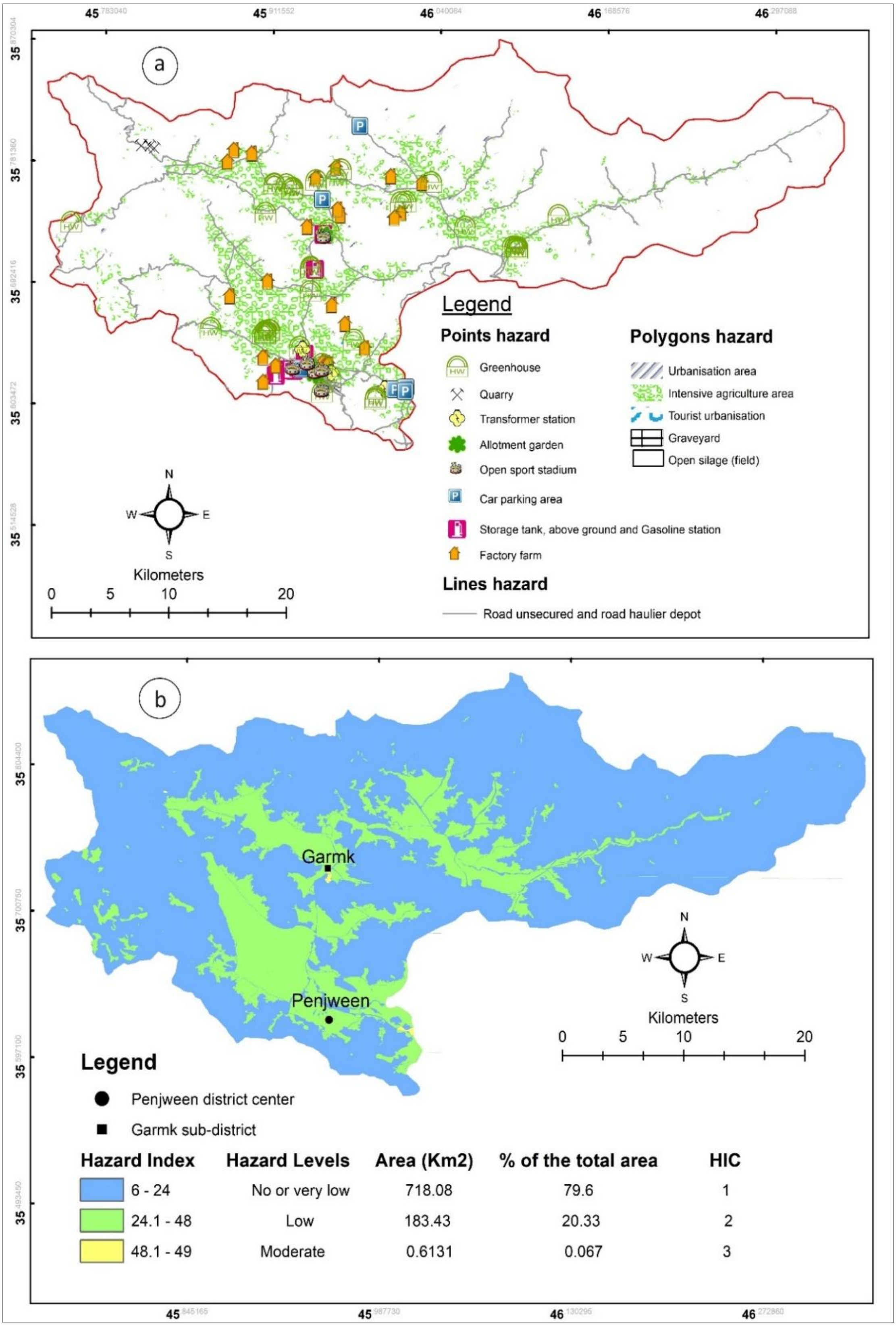

Figure 4. Hazard maps of the study basin (a) Unclassified, (b) Classified

Table 5. The DRASTIC index for the study area based on (Aller et al., 1987).

Classes	Standard DRASTIC-Model		Pesticide DRASTIC-Model	
	Area (Km^2)	**Percent area (%)**	**Area (Km^2)**	**Percent area (%)**
Very low	210	23.2	15.5	1.7
Low	431	47.7	216	23.9
Moderate	142	15.7	360	39.9
High	119	13	306	33.9
Very high	0	0	4.5	0.5

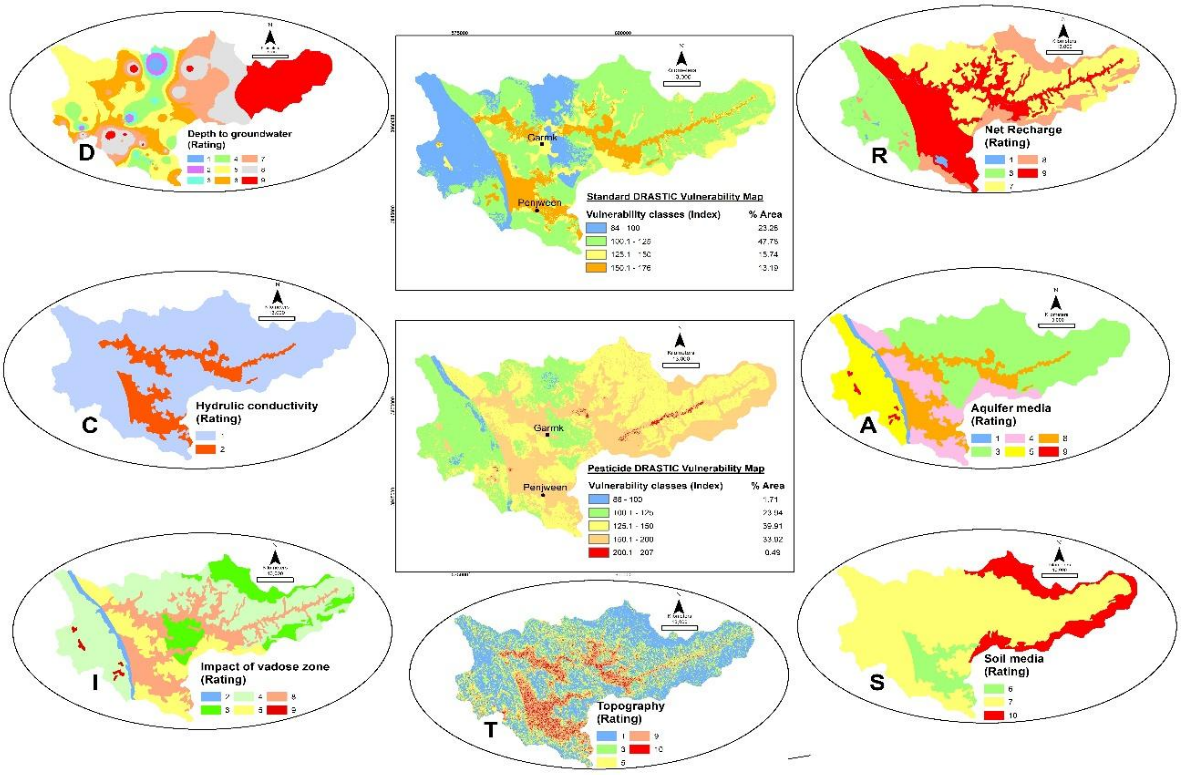

Figure 5. Standard and pesticide DRASTIC parameters of the study basin. D) groundwater depth, R) Net recharge, A) Aquifer media, S) Soil media, T) Topography, I) Impact of the vadose zone, and C) Hydraulic conductivity.

4.2.2 Pesticide DRASTIC map

The pesticide vulnerability index classifies areas into five levels: Very low, Low, Moderate, High, and Very high, with index values ranging from 88 to 207 (Figure 5). Most of the study area falls under moderate to high vulnerability levels, covering 360 Km² (39.9%) and 306 Km² (33.-9%) respectively (Table 5). The very high vulnerability class covers a minimum of 4.5 Km² (0.5%) of the total area. These zones, primarily in the southwestern and eastern parts of the basin, are associated with complex intergranular and fissured aquifers and should restrict agricultural activities especially if high rates of agrochemicals are used, due to the risk of groundwater pollution. The very low and low vulnerability classes occupied (15.5 Km^2) and (216 Km^2) or (1.7%) and (24%) of the total area respectively. These areas are predominantly complex aquifers with virtually impermeable layers, such as interbedded shale, marl, and chert, which offer protection and are mainly found around Garmk Town and in the northwestern and western parts of the study area. Therefore, areas with low vulnerability have been identified on the map and can be used to develop strategic agricultural activities to minimize the risk of contamination.

4.3. PO_4^{-3} concentration map

According to Iraqi guidelines (ICSD, 2009), the recommended concentration of PO_4^{-3} in groundwater is 0.4 mg/l. In the current study, PO_4^{-3} concentrations ranged from 0.01 to 4.86 mg/l. To validate the standard and pesticide DRASTIC scenarios, phosphate concentrations were sampled from 40 groundwater sources, as shown in Figures (6a) and (6b). 70% of the samples surpassed the permitted concentration levels set by Iraqi standards. Of these samples, 85% were located in areas identified as moderate to high vulnerability zones according to pesticide scenarios. Additionally, under standard scenarios, 55% were found in areas classified as moderate to high vulnerability zones. This confirms the accuracy of the standard and pesticide DRASTIC maps.

Figure 6c illustrates the spatial distribution of phosphate in groundwater, revealing high concentrations in two specific areas. In the eastern region, elevated phosphate levels likely stem from natural soil sources and igneous and metamorphic rocks. In the southern and southwestern regions, including the densely agricultural (Braim Awa Plain) and the urban area of Penjween Town, higher phosphate levels are probably due to extensive agrochemical use and potential leaks from municipal water and sewer systems. Unfortunately, these areas are situated on the intergranular aquifer within the study basin. High PO_4^{-3} levels in groundwater pose significant health risks, including kidney damage and osteoporosis (Bricker, 1972; Slatopolsky et al., 1971).

4.4. Risk intensity map

Following the guidelines of COST Action 620, the hazard map was combined with the standard and pesticide vulnerability maps to produce a risk intensity map, which assesses the potential impact of human activities. The risk map indicates that the study basin shows risk classes ranging from moderate to very low due to various hazard types. For the standard scenario (Figure 7a), the risk levels are as follows: 0.05% (0.5 Km^2) at very high risk, 0.07% (0.7 Km^2) at high risk, 1.4% (13.5 Km^2) at moderate risk, 9% (82 Km^2) at low risk, and 89% (805 Km^2) at no or very low risk. In the pesticide scenario (Figure 7b), 0.04% (0.2 Km^2) is at moderate risk, 4.7% (41.6 Km^2) is at low risk, and 95% (857.4 Km^2) is at no or very low risk. Fortunately, nearly the entire study area in both scenarios falls within the very low or low-risk zones for contamination sources.

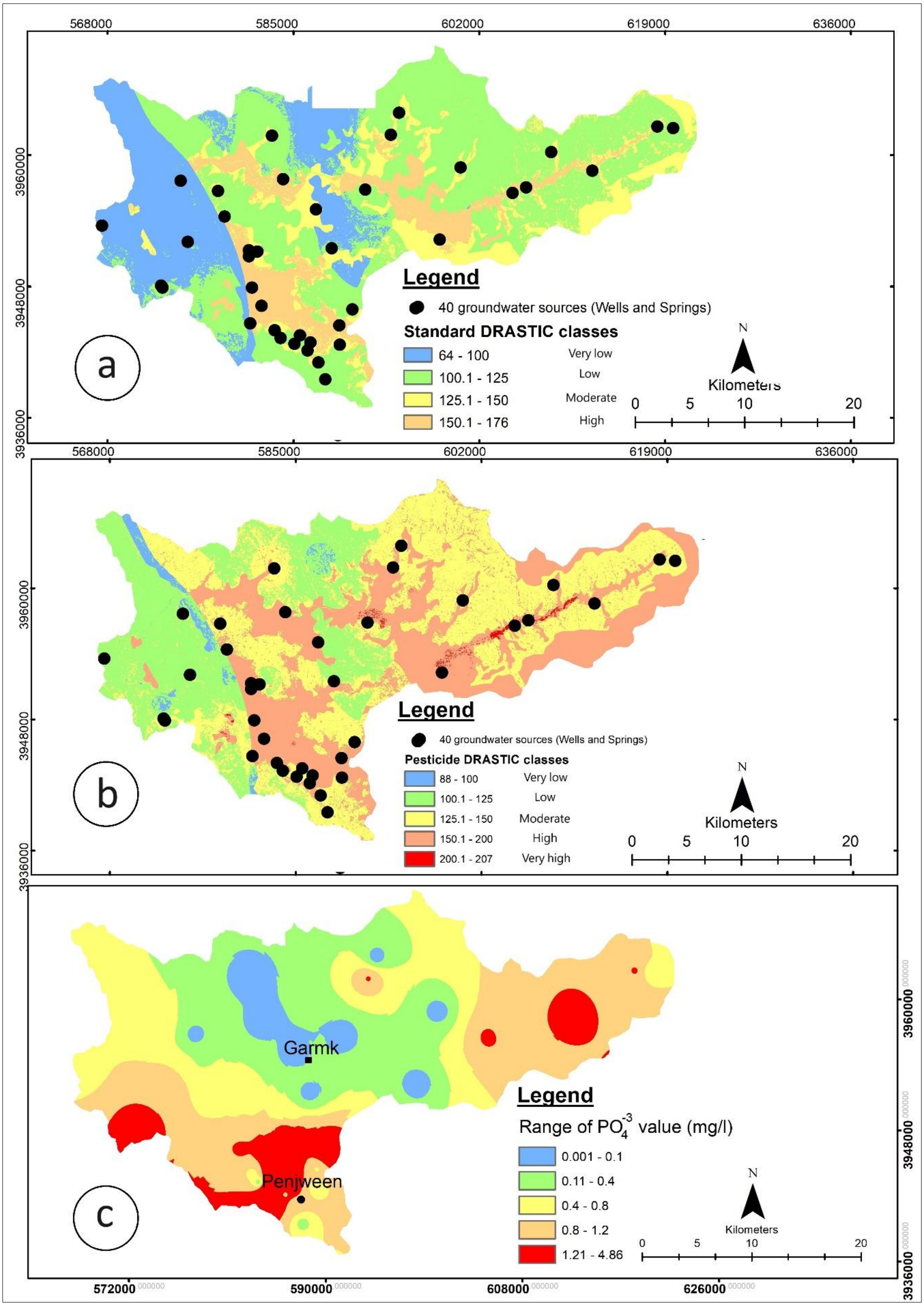

Figure 6. Location of sampling on scenarios (a) Standard (b) Pesticide (c) The spatial distribution of PO_4^{-3} concentration in the study basin.

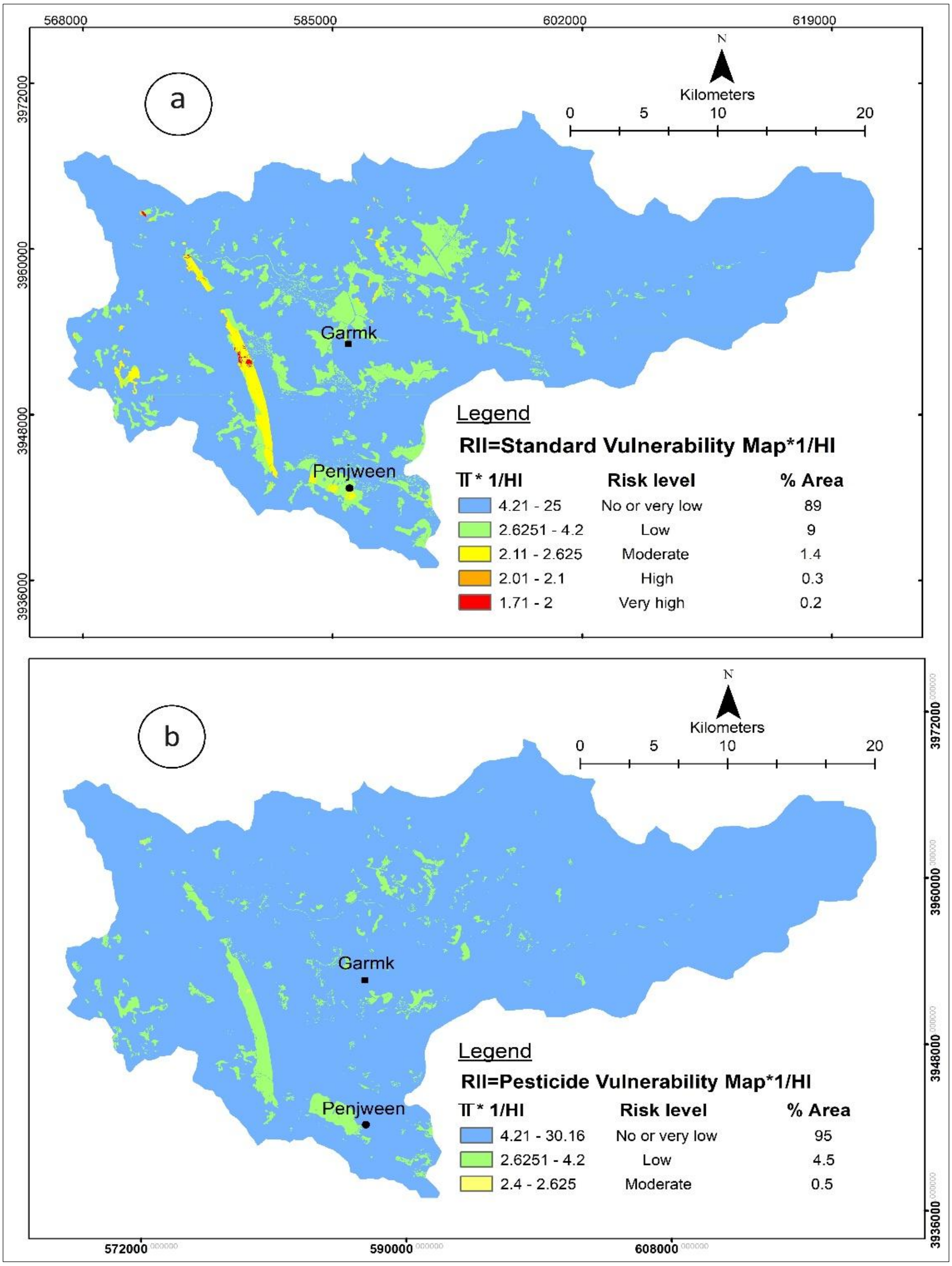

Figure 7. Risk intensity map of the study basin (a) Standard and (b) Pesticide.

5. Conclusions

The evaluation of groundwater vulnerability in the study basin, utilizing both standard and pesticide DRASTIC index maps, provided valuable insights. The standard DRASTIC index, with values ranging from 64 to 176, classified the area into four vulnerability classes: very low, low, moderate, and high. The very low and low vulnerability classes dominated, encompassing

23.2% and 47.7% of the area respectively. These regions, characterized by fissured aquifers with igneous and metamorphic rocks, are mainly situated in the hills and mountains. Conversely, areas with moderate (15.7%) and high (13%) vulnerability were identified in the Braim Awa Plain, Penjween Town, and near streams, where intergranular aquifers comprising pebble, gravel, sand, and silt are prevalent. The pesticide DRASTIC index, with values between 88 and 207, classified the area into five vulnerability levels: very low, low, moderate, high, and very high. Major classes of the study basin fell under moderate (39.9%) and high (33.9%) vulnerability levels. The very high vulnerability class, covering only 0.5% of the area, highlighted critical regions in the southwestern and eastern parts of the basin. These areas revealed high ratings in parameters such as net recharge, aquifer media, topography, and hydraulic conductivity, indicating a greater susceptibility to agriculture, industrial, and municipal pollutants. In these areas, agrochemicals should be limited to prevent groundwater contamination. The lack of effective water management plans, inappropriate land use practices, and improper use of agrochemicals exacerbate the situation. Additionally, there is a lack of awareness and support for farmers, leading to inadequate irrigation and drainage projects. Inappropriate solid waste disposal and the drilling of numerous unauthorized wells for public, industrial, and agricultural purposes further exacerbate the issue. The combined impact of these factors significantly strains the available water resources, posing a serious challenge to sustainable water management and environmental health. Without effective intervention, these issues are expected to increase in severity over time. Validation through phosphate (PO_4^{-3}) concentration measurements from 40 groundwater sources showed that 70 % of the samples exceeded the recommended Iraqi limits. High phosphate levels were predominantly found in areas with moderate to high vulnerability, confirming the reliability of the DRASTIC maps. Elevated phosphate levels in the eastern part were attributed to natural soil sources and igneous and metamorphic rocks. However, in the southern and southwestern parts, including Braim Awa Plain and Penjween Town, they may be linked to extensive agrochemical use and potential leaks from municipal water and sewer systems. The risk intensity maps indicated that most of the study basin falls within very low to low-risk zones for contamination in standard and pesticide scenarios. These findings underscore the importance of implementing targeted management strategies to mitigate groundwater pollution, especially in areas recognized as moderate to high risk. Implementing such ways is essential to ensure groundwater quality and protect public health in the basin. Future initiatives should prioritize enhancing monitoring systems, improving agrochemical management, and encouraging sustainable land and water use practices to ensure the long-term protection of water resources.

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About the author

Rebar Aziz Qaradaghy earned his bachelor's degree in 2007 and a master's degree in 2015 (Hydrogeology) from Sulaimani University. With over 14 years of experience at the Sulaimani Groundwater Directorate, he established and led the GIS unit starting in 2017. He has contributed to the development of numerous groundwater projects and supervised the drilling of many water wells. Currently, he is a PhD student in Water Resources at the College of Science, Department of Earth Sciences and Petroleum.

e-mail: rebarqaradaghy@gmail.com

Diary Ali Mohammed Al-Manmi, a professor in water resources (hydrogeology), graduated from the University of Baghdad. Currently; he is a Dean of the Department of Petroleum and Energy Engineering, Technical College of Engineering, Sulaimani Polytechnic University. He has 20 years of experience working in the field of hydrogeology, his research interest is in groundwater modeling, hydrogeochemistry, delineation of groundwater potential area, and recharge zones. He published twenty-three articles in international and local journals.

e-mail: diary.amin@spu.edu.iq

Dara Faeq Hamamin is a Professor in Hydrogeology and GIS, teaching at the College of Science, University of Sulaimani, Kurdistan Region, Iraq. He has published over 18 papers in national and international journals. His research interest is mainly focused in groundwater vulnerability, delineation of groundwater potential zones, and rainwater harvesting sites. He has been actively involved in lecturing undergraduate and postgraduate programs, covering subjects in hydrogeology, environmental geology, and GIS.

e-mail: dara.amin@univsul.edu.iq