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Comparative Examination of the DRASTIC and Susceptibility Index Approaches for Assessing Aquifer Vulnerability in Porous Media

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Abstract

Groundwater is becoming increasingly vulnerable to quality degradation. Several methods for assessing the vulnerability of groundwater to anthropogenic pollution have been developed over the last decade. To prevent groundwater pollution, political decision-makers and researchers frequently use these methods to identify vulnerable areas. This article presents two important methods for assessing the vulnerability of aquifers for resource protection (DRASTIC and the Susceptibility Index (SI)). As previous studies have indicated the difficulty of formulating a single technique for assessing groundwater vulnerability, different methods and techniques have been proposed. This article presents two methods, DRASTIC and the Susceptibility Index (SI), which we will examine in detail, focusing on their advantages and limitations. In this context, we introduce the importance of groundwater before discussing the concept of aquifer vulnerability. This is followed by a more detailed examination of the two methods, focusing on their advantages and limitations. Finally, the study provides an objective comparison of the two methods for assessing aquifer vulnerability.

Keywords

Groundwater Vulnerability Assessment, Quality, Pollution, Drastic, SI

1. Introduction

Groundwater is the world's largest accessible freshwater resource and an important resource for drinking water supply, irrigation, and industry, as well as for global food security (Sefie et al., 2015). It is particularly valuable in arid and semi-arid regions, where the availability of rainfall and surface water resources is limited (Li et al., 2015). However, in recent decades, groundwater has experienced quality deterioration due to human activities and natural environmental changes (Li, 2014; Vaux, 2011). For example, groundwater contamination due to poor management has been reported in Jordan (El-Naqa & Al-Shayeb, 2009), China (Wu & Sun, 2016; Zaisheng, 1998), America (Ayotte et al., 2015; Rattray, 2015), India (Ambast et al., 2006), Australia (McCallum et al., 2010), and South Africa (Nel et al., 2009). In this context, appropriate measures must therefore be taken to ensure groundwater quality and safety.

Assessing aquifer vulnerability provides one approach to optimizing and preserving water potential. Two main types of vulnerability are identified in the literature: specific vulnerability and intrinsic vulnerability (Civita, 1994; Schnebelen et al., 2002). Specific vulnerability refers to the vulnerability of groundwater to a given pollutant or group of pollutants, depending on the character of pollution sources and the land use. Specific vulnerability considers the diffusion properties of pollutants and their interaction with the different components of intrinsic vulnerability. The intrinsic (or natural) vulnerability is considered to explain the capacity of an aquifer system (e.g., hydrogeological, hydrological, and geological characteristics) to affect groundwater quality, according to temporal and spatial variations, because of human activity and/or natural processes. The specific vulnerability is viewed as evolving and characterized at a specific time, while the intrinsic vulnerability can be considered invariant in time.

Different methods have been developed around the world for specific and intrinsic vulnerability mapping and assessment. Such methods involve combining various hydrogeological/geological settings to generate maps depicting areas with different levels of vulnerability, which are designated by colors, patterns, or scores. According to Katyal et al. (2017), these types of maps contribute to decision-making procedures for the conservation and monitoring of groundwater quality.

French researchers elaborated the first vulnerability maps in the early 1970s (Albinet & Margat, 1970). The principle of their elaboration consisted essentially of classifying sites according to the properties and geometry of the aquifer environments. Over the years, various methods have been proposed and tested in order to achieve a simple and precise characterization of vulnerability. These methods can be classified into three: 1) statistical methods, including artificial intelligence; 2) process-based simulation methods or methods of physical modeling; and 3) parametric methods or index and overlay methods. These three vulnerability assessment approaches are different in their conceptualization and choice of factors, as well as in their formulation.

Statistical methods rely on observation rather than expert opinion. They link anthropogenic and physiographic factors. Based on the observed contamination information in the area, statistical methods can be applied to find the relationship between contamination factors and survey data (Zhao & Pei, 2012) by identifying a correlation between environmental or social variables that may explain the contamination. Therefore, the statistical methods as per Zhao and Pei (2012) seek to identify the variables that may define the probability of contamination of water resources. Process-based simulation methods are based on hypotheses verified by analytical or mathematical models that provide an approximate view of the behavior of substances in the subsurface. Index and overlay methods incorporate all water stakeholders and thus integrate physical, eco-environmental, and socioeconomic factors that influence groundwater vulnerability and are weighted by expert opinion (Alessa et al., 2008; Yanhui et al., 2012). Index and overlay methods are known to be the most widely used due to their simplicity (Masetti et al., 2009). They are particularly suited to the use of a geographic information system (GIS), which provides useful tools for overlaying and integrating the various multiple maps (Kaliraj et al., 2015; Saida et al., 2017). Various overlay and indexing methods have been developed for vulnerability assessment of aquifers in porous media, among them: DRASTIC (Aller et al., 1987), GOD (Duijvenbooden & Waegeningh, 1987), SI (Ribeiro, 2000), AVI (Stempvoort et al., 1993), and SINTACS (Civita & De Maio, 1997), among others. DRASTIC and SI are the most widely used and effective index overlay methods for quantifying groundwater vulnerability in porous media, due to their good definition of groundwater vulnerability, minimal data demand, and ease of use. Further to the development of the database associated with GIS, the simple calculations of the DRASTIC and SI models are physically meaningful and well-adapted to large-scale problems. However, to ease the decision-making in the early project launch stage, a better understanding of DRASTIC and SI advantages and limitations can save energy, time and money. Hence, there is the need to compare the DRASTIC and SI approaches to vulnerability assessment to identify the applicability of each to help guide resource management and future land use.

2. Potential Threats to Groundwater

2.1. Groundwater Physico-Chemical Characteristics

Nowadays, for many different reasons, groundwater is contaminated, creating a serious health hazard in both man and animals (Kazi et al., 2009). Major contaminants comprise nitrates (Mahvi et al., 2005), heavy metals (Taghinia Hejabi et al., 2011), and organic compounds (Manecki & Gałuszka, 2012). **Table 1** summarizes different groundwater composition ranges found across countries. As indicated in the literature, there is a large variation between groundwater in terms of values and concentrations of constituents.

Generally, groundwater has potential hydrogen (pH) values averaging between 6.6 and 8.3, indicating a neutral to slightly alkaline nature of groundwater. According to WHO, the pH of water does not have a direct effect on human health; however, it is related to other chemical constituents of water in general (Mostafa et al., 2017; Saalidong et al., 2022).

Table 1. Variation of selected parameters in different groundwaters.

(a)

PARAMETER	GROUNDWATER SITE					
	MOROCCO (Bahir et al., 2020)	CHINA (Ren et al., 2021)	IRAN (Badeenezhad et al., 2020)	INDIA (Kumari & Rai, 2020)	ALGERIA (Kouadra & Demdoum, 2020)	PAKISTAN (Talib et al., 2019)
pH	7.6 ± 0.3	8.2 ± 0.3	7.8 ± 0.2	8.3 ± 0.3	6.7 ± 1.6	7.4 ± 0.3
EC	1984.1 ± 721.3	-	-	2806.0 ± 2376.0	1383.7 ± 954.9	1571.0 ± 1061.9
Temperature	20.9 ± 2.1	-	-	-	20.9 ± 8.6	-
TDS	-	829.9 ± 659.1	614.5 ± 200.5	-	1641.6 ± 1005.6	993.9 ± 677.5
Turbidity	-	-	-	-	-	7.8 ± 27.3
Total Hardness	-	389.2 ± 232.2	421.0 ± 112.6	946.1 ± 118.2	-	421.1 ± 253.0
Alkalinity	-	-	-	-	-	5.7 ± 3.7
Arsenic	-	-	-	-	-	22.0 ± 48.3
Zinc	-	-	-	-	-	-
Iron	-	-	-	-	-	0.1 ± 0.2
Manganese	-	-	-	-	-	-
Magnesium	72.0 ± 44.7	59.2 ± 52.1	54.4 ± 19.0	115.0 ± 167.2	62.2 ± 34.2	55.4 ± 34.3
COD	-	1.2 ± 1.3	-	-	-	-
Nitrate	33.9 ± 15.8	23.3 ± 41.7	25.6 ± 15.5	84.0 ± 132.7	-	0.9 ± 1.6
Fluoride	-	0.8 ± 0.6	0.6 ± 0.1	1.0 ± 1.8	-	0.4 ± 0.5
Phosphate	-	-	-	-	-	-
Sodium	234.7 ± 108.6	149.4 ± 152.0	49.7 ± 22.6	392.6 ± 49.1	270.7 ± 227.8	165.2 ± 151.8
Sulphate	130.6 ± 111.9	191.9 ± 246.3	152.6 ± 88.6	378.0 ± 559.4	680.9 ± 529.3	169.9 ± 140.1
Chloride	527.8 ± 288.3	107.3 ± 120.1	71.0 ± 40.9	648.0 ± 841.3	163.9 ± 128.3	209.8 ± 186.3
Carbonate	-	4.0 ± 7.1	-	-	-	-
Bicarbonate	489.7 ± 190.9	425.8 ± 180.6	301.0 ± 60.4	311.0 ± 165.0	296.4 ± 107.5	308.9 ± 170.3
Potassium	10.7 ± 14.1	2.0 ± 2.1	-	-	10.7 ± 3.7	3.5 ± 5.2
Calcium	150.7 ± 43.4	57.6 ± 27.9	79.0 ± 20.5	83.7 ± 119.3	159.4 ± 140.4	76.5 ± 49.7

(b)

PARAMETER	GROUNDWATER SITE					
	SOUTH AFRICA (Elumalai et al., 2020)	GHANA (Loh et al., 2020)	NIGERIA (Egbueri, 2019)	IRAQ (Ismail et al., 2020)	ITALY (Tiwari et al., 2019)	QATAR (Ahmad et al., 2020)
pH	6.7 ± 6.6	6.9 ± 0.6	6.0 ± 0.5	7.3 ± 0.2	7.3 ± 0.3	7.3 ± 0.2
EC	344.0 ± 217.0	429.0 ± 196.0	127.5 ± 83.5	3153.4 ± 2273.4	3979.0 ± 2635.0	7.3 ± 4.7

Continued

Temperature	-	-	-	-	21.5 ± 1.4	-
TDS	220.0 ± 139.0	-	67.8 ± 38.7	2673.5 ± 2556.7	2276.0 ± 1490.0	5038.1 ± 3367.7
Turbidity	-	-	0.4 ± 0.3	-	-	-
Total Hardness	114.0 ± 67.0	158.0 ± 47.7	53.3 ± 31.4	-	-	2120.2 ± 1049.3
Alkalinity	-	178.3 ± 57.5	-	-	-	-
Arsenic	-	<0.01 ± 0.01	-	--	-	0.002 ± 0.0
Zinc	-	-	0.01 ± 0.01	-	-	0.01 ± 0.01
Iron	-	0.2 ± 0.5	0.04 ± 0.05	-	-	0.004 ± 0.02
Manganese	-	0.1 ± 0.1	0.1 ± 0.03	-	-	0.001 ± 0.001
Magnesium	15.0 ± 9.0	18.0 ± 6.4	22.0 ± 11.1	84.6 ± 58.8	95.0 ± 63.0	169.1 ± 95.1
COD	-	-	-	-	-	-
Nitrate	3.0 ± 2.0	0.4 ± 0.8	13.2 ± 1.0	3.7 ± 2.3	95.0 ± 57.0	36.3 ± 27.6
Fluoride	-	0.8 ± 0.4	--	-	-	3.8 ± 1.6
Phosphate	-	0.1 ± 0.1	0.4 ± 0.4	-	-	-
Sodium	18.0 ± 11.0	31.0 ± 17.7	8.9 ± 5.1	298.4 ± 216.8	549.0 ± 437.0	1466.0 ± 1244.0
Sulphate	6.0 ± 4.0	12.8 ± 14.5	7.6 ± 3.8	658.4 ± 483.6	155.0 ± 102.0	4977.2 ± 2491.2
Chloride	49.0 ± 18.0	18.8 ± 13.1	17.3 ± 8.6	390.4 ± 286.6	974.0 ± 748.0	6289.5 ± 6747.5
Carbonate	-	-	-	-	-	-
Bicarbonate	105.0 ± 66.0	217.5 ± 70.2	57.4 ± 38.5	251.8 ± 187.0	247.0 ± 104.0	-
Potassium	9.0 ± 3.0	4.9 ± 1.7	1.1 ± 0.4	14.9 ± 28.2	23.0 ± 28.0	90.2 ± 56.9
Calcium	21.0 ± 13.0	33.6 ± 14.4	35.8 ± 16.3	183.3 ± 171.0	133.0 ± 57.0	570.2 ± 277.1

(c)

PARAMETER	GROUNDWATER SITE					
	ROMANIA (Dippong et al., 2019)	FRANCE (Lorette et al., 2021)	SRI LANKA (Balasooriya et al., 2020)	GREECE (Papazotos et al., 2019)	MEXICO (Hernández-Mena et al., 2021)	ARMENIA (Ghazaryan et al., 2020)
pH	6.3 ± 0.3	7.5 ± 0.1	6.6 ± 0.4	7.0 ± 0.2	6.6 ± 0.8	6.9 ± 0.1
EC	642.0 ± 154.0	378.0 ± 37.6	376.0 ± 191.0	2558.9 ± 1067.2	243.3 ± 115.3	2439.0 ± 1014.3
Temperature	-	14.2 ± 0.7	29.1 ± 0.9	-	20.4 ± 3.7	-
TDS	-	-	210.0 ± 98.0	1453.5 ± 632.9	123.7 ± 59.6	1683.3 ± 733.4
Turbidity	1.1 ± 1.2	-	-	-	1.9 ± 6.2	-
Total Hardness	-	-	154.0 ± 71.0	-	88.4 ± 49.1	-
Alkalinity	-	-	161.0 ± 83.0	-	112.2 ± 54.2	-
Arsenic	0.0 ± 0.0	-	-	-	0.004 ± 0.009	-

Continued

Zinc	0.2 ± 0.0	-	-	-	0.02 ± 0.1	-
Iron	0.3 ± 0.0	-	-	-	0.1 ± 0.2	-
Manganese	0.1 ± 0.0	-	-	-	0.02 ± 0.2	-
Magnesium	-	11.0 ± 12.0	15.1 ± 9.6	34.2 ± 17.3	11.4 ± 7.1	164.3 ± 77.3
COD	1.1 ± 0.6	-	-	-	9.3 ± 38.4	-
Nitrate	42.0 ± 32.0	-	0.7 ± 0.6	44.2 ± 45.2	10.0 ± 16.5	-
Fluoride	-	-	0.9 ± 1.0	-	0.4 ± 0.0	-
Phosphate	-	-	0.8 ± 0.4	-	0.8 ± 0.5	-
Sodium	-	4.9 ± 0.7	31.2 ± 14.9	214 ± 147.6	17.2 ± 9.5	186.5 ± 69.9
Sulphate	-	15.9 ± 5.2	21.2 ± 15.0	146.3 ± 88.1	16.4 ± 17.6	-
Chloride	37.4 ± 23.5	6.4 ± 1.0	52.1 ± 18.7	508.6 ± 325.2	3.8 ± 5.4	230.1 ± 149.3
Carbonate	-	-	-	-	-	-
Bicarbonate	-	223.0 ± 21.0	-	309.5 ± 185.4	-	488.5 ± 97.9
Potassium	-	2.6 ± 0.3	0.6 ± 0.3	6.7 ± 4.3	0.5 ± 0.6	8.7 ± 4.9
Calcium	-	62.3 ± 7.4	30.7 ± 17.9	202.4 ± 90.5	16.6 ± 10.2	158.3 ± 58.3

(d)

PARAMETER	GROUNDWATER SITE	
	BANGLADESH (Ahmed et al., 2019)	EGYPT (El-Rawy et al., 2019)
pH	5.7 ± 1.0	7.8 ± 0.6
EC	292.2 ± 191.5	1544.0 ± 945.8
Temperature	25.6 ± 0.8	-
TDS	-	1034.0 ± 633.7
Turbidity	-	-
Total Hardness	-	381.1 ± 357.9
Alkalinity	-	-
Arsenic	0.04 ± 0.05	-
Zinc	-	-
Iron	8.7 ± 6.6	-
Manganese	0.2 ± 0.2	-
Magnesium	4.8 ± 4.3	53.9 ± 45.5
COD	11.0 ± 11.5	-
Nitrate	5.7 ± 7.7	-
Fluoride	-	-

Continued

Phosphate	-	-
Sodium	39.5 ± 24.3	179.1 ± 129.1
Sulphate	1.4 ± 1.6	144.9 ± 118.1
Chloride	21.2 ± 26.3	346.6 ± 330.6
Carbonate	-	-
Bicarbonate	123.7 ± 82.6	198.8 ± 84.6
Potassium	2.3 ± 1.0	1.3 ± 1.0
Calcium	7.6 ± 6.5	63.8 ± 83.0

Electrical conductivity (EC) of groundwater is an indicator of the presence of metal ions and inorganic elements (Egbueri, 2019; Lin & Chang, 2000). Gueddari et al. (2022) and Qureshi et al. (2011) have indicated that the electrical conductivity of groundwater is related to the level of mineralization and provides information on salinity levels. Additionally, a relationship between electrical conductivity and total dissolved solids has been evidenced by some researchers (Thirumalini & Joseph, 2009), which are both indicators of salinity levels. Various extremes of mean electrical conductivity (EC) and total dissolved solids (TDS) values were found in the groundwater selected for this study, especially in Italy and Qatar with mean values of 3979 µS/cm and 5038.1 mg/l, respectively. According to Ismail et al. (2020); Kumari & Rai (2020), the reason for the high salinity of groundwater in these areas of semi-arid climatic conditions is due to the evapotranspiration exceeding the precipitation, and the lack of drainage. Furthermore, it was found that agricultural activities involving the use of fertilizers and irrigation with highly saline water can result in a concentration of salts in the soil due to high evaporation, which can lead to the leaching of salts and nutrients into the aquifer (Ahmad et al., 2020). Alfarrah & Walraevens (2018) and Barlow & Reichard (2010) studies have indicated that extensive groundwater extraction can result in increased EC due to saltwater intrusion in coastal areas. Temperature is an important parameter which controls micro-organism activity and chemical equations (Schürch et al., 2018). In this review, the average groundwater temperature is between 14.2 and 29.1˚C. An increase in water temperature can, for example, lead to a decrease in the concentration of dissolved oxygen, favoring the presence of pathogenic bacteria and thus causing a decrease in the microorganisms that indicate the good quality of the resource (Garnier, 2012). The temperature of groundwater is related to climate and hydrogeology. Groundwater loses or gains heat from the ground surface. According to Taylor and Stefan (2009), the average annual ground surface temperature is controlled by climate and land use (surface cover). If climate and land use do not vary over time, the average annual groundwater temperature and the average annual ground surface temperature are theoretically identical.

The average chemical oxygen demand (COD) in groundwater for this study is from 1.1 to 11 mg/l. The presence of COD in water indicates organic matter content, which is related to a richer pathogenic microflora (Dippong et al., 2019). These authors add that COD is an indirect chemical index of water pollution by inorganic oxidizable substances such as S^{2-}, ferrous salts, and NO_2^-. Previous studies by Ahmed et al. (2004) and Halim et al. (2010) found that the presence of organic matter in sediments can play an important role in the creation of anaerobic environments in groundwater.

Turbidity in groundwater results from an extremely fine colloidal suspension in the form of finely divided matter (organic and inorganic), microorganisms such as plankton, and clay (Majeed & Nashaat, 2022). The average groundwater turbidity in selected groundwater ranged from 0.4 to 7.8 NTU. This indicates that dissolved solids in the groundwater are low and that microorganisms have difficulty in multiplying or resisting disinfection (Egbueri, 2019).

The total hardness (TH) varies widely between countries. Average values are between 53.3 and 2120.2 mg/l. Physically, hardness can depict the resistance of water to lathering soap (Todd, 2008). According to Saana et al. (2016), TH chemically indicates the total concentration of Mg^{2+} and Ca^{2+} in mg/l of $CaCO_3$ equivalent. Hard water consumption can cause white incrustations on boilers and cooking utensils (Kaushik et al., 2002) and can scale water pipes and water heaters, and can require more soap for laundry (Akram & Rehman, 2018). Hard water is also responsible for anencephaly, urolithiasis, some cardiovascular disorders, and some types of cancer (Marghade, 2020).

Generally, about 95% of the ions encountered in groundwater are Mg^{2+}, Ca^{2+}, K^+, Na^+, NO_3^-, HCO_3^-, SO_4^{2-}, and Cl^- (Sundaram et al., 2009). According to Abdel-Satar et al. (2017), the main source of ions in groundwater is rock lithology, in contrast to anthropogenic sources.

As with total hardness (TH), the average concentration of calcium and magnesium ions in groundwater varies widely, from 7.6 to 570.2 mg/l and from 15 to 169.1 mg/l, respectively. The presence of calcium ions in groundwater can be naturally associated with the dissolution of silicate, phosphate, and sulfate minerals, and the dissolution of carbonate minerals (Cobbina et al., 2012). The presence of magnesium in groundwater can be attributed to geological sources such as biotite, pyroxene, and dolomite (Saana et al., 2016).

Average values of alkalinity are fairly low, with a peak average of 178.3 mg/L. Groundwater alkalinity is principally due to the presence of ions such as OH^-, CO_3^{2-}, or HCO_3^- (Wolf-Gladrow et al., 2007). Among these ions, bicarbonate is the main form because it is formed in large quantities by the action of carbonates on the basic materials of the soil (Kumari & Rai, 2020). Bicarbonate is naturally found in water, mainly through the CO_2 dissolution of carbonate-containing minerals or by the combination of rainwater and CO_2 (Ismail et al., 2018).

Average nitrate (NO_3^-) concentrations in groundwater range from 0.4 to 95 mg/l, while the average phosphate content is low and varies from 0.1 to 0.8 mg/l. Nitrates and phosphates are the major plant nutrients derived from fertilizers

(Egbueri, 2019). NO_3^- provides favorable growing conditions for algae and other aquatic plants, which use and deplete oxygen in the water, rendering it tasteless (Dippong et al., 2019). High nitrate contents in drinking water result in substantial health risks for pregnant women and infants and contribute to stomach cancer incidence (Adimalla, 2019; Ward et al., 2018). Further, the presence of high NO_3^- in water may influence organisms by blocking hemoglobin and producing methemoglobin (Dippong et al., 2019). Under natural conditions, the concentration of nitrates does not exceed 10 mg/l in water as reported by Cushing et al. (1973). NO_3^- pollution is principally driven by the decomposition of organic matter (Bahir et al., 2020), animal and human wastes, urban domestic sewage, intense fertilization, septic tank effluents (Zhang et al., 2014). NO_3^- leakage to groundwater over time is related to the geological and hydrogeological structure of an area (Racoviteanu, 2016). NO_3^- is highly mobile once it reaches groundwater (Eary et al., 1989), hence the load is very rapidly transferred.

Chloride (Cl^-) mean concentrations in groundwater vary widely from 3.8 to 6289.5 mg/L. Chlorides are common constituents of natural water (Ahmad et al., 2020). According to Adimalla and Venkatayogi (2018), the salty taste and laxative effects of drinking water may be due to high concentrations of Cl^-. Natural sources of Cl^- contained in groundwater include saline seeps, water-rock interactions, and rainwater, while anthropogenic sources include gypsum-based fertilizers (Vengosh et al., 2002), municipal landfill leachate, wastewater pollutants, industrial facility effluents, and road salt (Srinivasamoorthy et al., 2014).

Mean sulfate (SO_4^{2-}) values in groundwater show a wide range, from 1.4 to 4977.2 mg/l. High concentrations of SO_4^{2-} in groundwater result from natural sources such as the dissolution of anhydrite and gypsum rocks, and from anthropogenic sources such as fertilizers from agricultural activities (Czerewko et al., 2003). Alternatively, according to Egbueri (2019), low sulfate levels indicate that the investigation area is not an industrial site where higher concentrations are expected due to industrial processes and emissions. According to Ghalib (2017), SO_4^{2-} in water induces metal corrosion in the distribution system with low-alkalinity water.

Sodium (Na^+) and potassium (K^+) contents have mean values ranging from 4.9 to 1466 mg/l and 0.5 to 90.2 mg/l, respectively. Generally, Na^+ and K^+ ions in the GW are associated with each other, but the level of Na^+ is higher than that of K^+ (Al Suhaimi et al., 2019). Na^+ content may originate from the dissolution of sodium-bearing minerals, including sodium plagioclases such as albite (Egbueri, 2019). Kumar et al. (2009) and Meybeck (1987) reported that a Na/Cl ratio greater than 1 indicates that sodium ions are derived from silicate weathering. K^+ in groundwater: it can naturally result from feldspar weathering in igneous rocks and silicate and clay mineral weathering in sedimentary rocks (Ahmad et al., 2020). In addition, chemicals from fertilizers and industries are essential sources of K^+ in groundwater (Mallick et al., 2018). Trace element concentrations in the groundwater are mostly less than one mg/L (Ahmad et al., 2020; Ahmed et al., 2019; Dippong et al., 2019; Egbueri, 2019; Hernández-Mena et al., 2021; Loh et al., 2020; Talib et al., 2019).

Trace elements represent insoluble materials that are often suitable for metal precipitation in an alkaline environment (El gawad et al., 2008). Common metals present in the groundwater include iron, manganese, zinc, arsenic, and fluoride. According to Dippong et al. (2019), a relatively high amount of iron (Fe) in drinking water has no harmful effects on the human body, but can result in a metallic taste and an opalescent yellow color. High manganese (Mn) content forms brown to black deposits and gives a specific muddy odor and metallic taste, which is easily confused with hydrogen sulfide (Dippong et al., 2019). The presence of zinc (Zn) is beneficial to both humans and other ecological entities, although at higher levels it can be harmful to human biological systems (Adeyemi & Ojekunle, 2021). Arsenic (As) is one of the carcinogenic elements present in groundwater, resulting from both natural processes and human activities (Massoudinejad et al., 2020; Paydar et al., 2020). Regarding fluoride, Ali et al. (2016) highlighted fluoride-related health problems such as skeletal and dental fluorosis in humans, which in turn have serious socioeconomic implications.

Water contamination and human health are interrelated (Khan et al., 2009). Consumption of contaminated water may result in serious human health hazards. In 2002, a study in Bangladesh reported that tens of millions of people were poisoned to varying degrees by arsenic in well water (Harvey et al., 2002). A study by Nyanganji et al. (2011) conducted on the groundwater quality of Dass town in Nigeria found high concentrations of manganese, calcium carbonate (total water hardness), and E. coli that exceeded the safe WHO and SON safe drinking standards. Accordingly, water-borne diseases were observed at the Dass General Hospital (about 110 cholera cases, 3345 cases of diarrhea, 1522 cases of dysentery, and 1527 cases of typhoid).

In Togo, in the district of Adakpamé located in the commune of Lomé, it has been reported that water consumption from wells and boreholes is responsible for various microbial diseases, such as cholera, typhoid fever, bacillary dysentery, diarrhea and gastroenteritis, hepatitis A and E, and amoebic dysentery (Sokegbe et al., 2018).

2.2. Major Groundwater Contamination Sources

Groundwater contaminants have different sources (**Figure 1**). Some are of human origin; for example, saltwater intrusion along coastal areas (Alfarrah & Walraevens, 2018; Mtoni et al., 2013; Xu et al., 2021) and nitrate pollution caused by agricultural activities and improper construction of septic tanks (Almasri & Kaluarachchi, 2004; Corniello et al., 2007; Pastén-Zapata et al., 2014), while others are of natural origin, such as the solubilization of components like fluoride (F^-) (Adimalla et al., 2019; Kumar et al., 2018; Li et al., 2019).

2.2.1. Landfill Leachate as a Threat to Groundwater

Exponentially more solid waste is generated each year as a result of rapid population growth, industrial development, and urbanization. However, rainwater percolates through solid waste in landfills and generates a toxic liquid called landfill leachate with significant amounts of organic matter, inorganic salts, heavy metals, and ammonia nitrogen (Costa et al., 2019). Leachate composition principally depends on the amount of precipitation, the source of the landfill waste, and the age of the landfill.

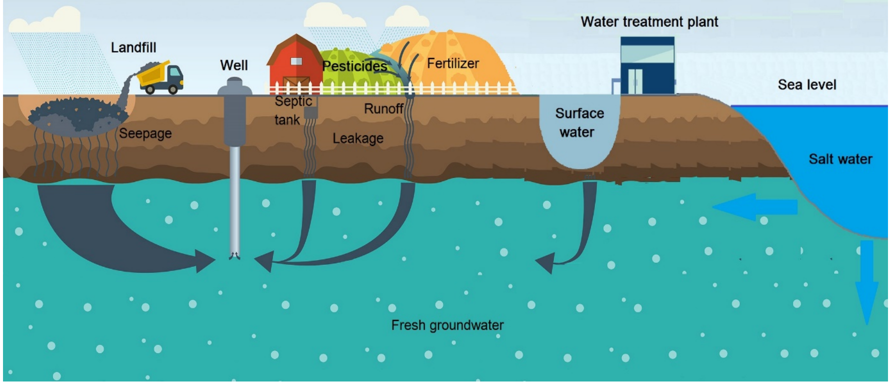

Figure 1. Main sources of groundwater contamination.

2.2.2. Nutrient and Pesticide Inputs by Agricultural Practices

Nutrient contamination of groundwater, especially nitrate (NO_3^-), is increasing in agricultural areas owing to excessive application of inorganic and organic nitrogen fertilizers (Shishaye, 2015; Xue et al., 2009). As a highly soluble substance, nitrate diffuses easily through the vadose zone before reaching groundwater. The nitrate, upon frequent use in agricultural landscapes, can accumulate significantly and remain in groundwater for decades (Sasakova et al., 2018).

Based on their widespread agricultural use and high mobility in the environment, some pesticides, such as atrazine and its derivatives, Atrazine-desisopropyl and desethyl-atrazine, are common contaminants of groundwater (APVMA, 2008; Giddings, 2005). Once atrazine enters an aquifer system, it persists longer than in surface water and soil due to the lack of photodegradation and generally anaerobic conditions (Schult, 2016). Within an aquifer, atrazine has a 2 - 18-month-long effective half-life (Giddings, 2005). Further groundwater contamination concerns include persistent pesticides such as hexazinone and bromacil, both of which have high mobility in groundwater (Shaw et al., 2012). Pesticides, once dissolved in groundwater, are also able to move through the hydrologic system and potentially affect the environment (APVMA, 2008).

2.2.3. Industrial Wastewater

Industrial wastewater is one of the major concerns associated with the rapid industrialization in the world today. Industrial effluents are characterized by significant amounts of organic and inorganic chemicals and their derivatives (Bougherira et al., 2014). Moreover, most industries are quite small and do not have sewer lines. To mitigate the negative effects of the hazardous components in industrial wastewater, adequate treatment of the effluent is mandatory prior to its release into water bodies or onto the land. However, Bougherira et al. (2014) report that most industries lack adequate treatment plants. Therefore, highly colored and toxic chemical effluents reach the river. According to Malik et al. (2019), discharges from nickel and other metal-plating industries are seriously impairing the land. Common heavy toxic metals in wastewater are chromium (Cr), arsenic (As), cadmium (Cd), mercury (Hg), zinc (Zn), copper (Cu), cobalt (Co), and nickel (Ni) (Gardea-Torresdey et al., 2005).

2.2.4. Septic Tank Leaks

Urbanization is a pervasive global trend. About 50% of the world's population is in urban areas, with a projection of 60% by 2030, according to Burns et al. (2005). Residents around major municipalities and in rural areas with no access to public sewage systems for latrine and kitchen discharges are expected to eliminate wastewater on-site.

A septic tank is one of the most common methods of on-site wastewater management. Septic tanks, as a means of wastewater disposal in homes, however, may have a major impact on groundwater. This is an issue in many countries. Groundwater is considered a source of local and regional groundwater contamination in Nigeria (Adetunji & Odetokun, 2011), in the United States (Katz et al., 2011), in Ghana (Takal & Quaye-Ballard, 2018), and in China (Lu et al., 2008).

Septic tank wastewater often contains nitrogen, which is a major concern because of public health concerns and its potential adverse ecological effects (Yang et al., 2017). Of the nitrogen species, nitrate (NO3) is the most prevalent. Generally, NO3 contamination of groundwater results from nitrogen movement in the unsaturated zone (vadose) and transformation processes in the unsaturated or saturated zones (Tang et al., 2004).

2.2.5. Seawater Intrusion

In coastal areas, seawater intrusion has been reported in many areas as a global environmental concern, including the Mekong Delta in Vietnam (Xiao et al., 2021), Ibeno in Southeastern Nigeria (Inim et al., 2020), the northwest coast of Oman (Ahmed & Askri, 2016), North Sinai in Egypt (Gad & Khalaf, 2015), and Cyprus (Kathijotes & Panayiotou, 2013). Research on the mechanisms and impacts of seawater intrusion has been conducted lately in various locations. Hydrochemical and isotopic parameters of groundwater have been applied by Galliari et al. (2021) in South American coastal wetlands for the purpose of examining the dominant processes of groundwater salinity. Based on a series of geostatistical methods, Sivakarun et al. (2020) investigated the dominant factors of hydrochemical processes in shallow coastal groundwater in India. In a thorough analysis of anthropogenic and natural processes governing groundwater salinization, Telahigue et al. (2020) evaluated the sources of different groundwater bodies based on the hydrogeochemical and isotopic characteristics of unconfined groundwater on Djerba Island in southeastern Tunisia.

Seawater intrusion is often closely linked to anthropogenic activities in densely populated areas. Salinization of superficial aquifers can result in the salinization of soils, with consequent decreases in crop yields, deterioration of vegetation, and gradual environmental decline, along with a decline in the quality of farmlands (Shi & Jiao, 2014). Furthermore, seawater intrusion induces direct pollution of groundwater, which makes it unsuitable for industrial production, irrigation, and consumption. Global warming induces a rise in sea level that may lead to large-scale seawater intrusion. Thus, it is necessary to review the future trends of seawater intrusion, the mechanism of occurrence, and the current status to better identify the inevitable risks of seawater intrusion that will arise in different regions. Based on Kamal et al. (2020), the significant increase in Cl and TDS levels in coastal groundwater towards the coastline is a good indicator of seawater intrusion. However, water-rock interaction is affecting the salinity of groundwater (Nefzaoui et al., 2023; Vespasiano et al., 2021).

2.3. Impacts of Contaminated Groundwater

Groundwater pollution can affect socioeconomic development, environmental quality, and human health. Numerous studies reveal, in particular, a health risk to human populations from significant levels of persistent organic pollutants (metals, fluoride, and nitrate) (Sunitha et al., 2022). Infants and children are particularly vulnerable to the effects of these contaminants (Adimalla et al., 2020; Kadam et al., 2021; Mohammadpour et al., 2022; Shalyari et al., 2019; Su et al., 2021; Wu et al., 2019; Yin et al., 2020). High nitrate concentrations in drinking water for formula preparation are responsible for infant methemoglobinemia, also known as "blue baby syndrome." In addition, irrigation using groundwater contaminated with wastewater containing persistent contaminants such as heavy metals is likely to cause vegetables and grains to accumulate toxic elements, thus posing risks to human health (Kumar et al., 2022; Minhas et al., 2022; Pratap et al., 2021).

Groundwater pollution can have a negative impact on the quality of forests and land. In fact, groundwater contamination is likely to promote the degradation of soil quality. According to Wu et al. (2014), the high salinity of groundwater is one of the main factors of soil salinization in many agricultural areas in arid regions. Besides, a nuisance to vegetation growth may be due to the accumulation of soluble salts and some contaminants, including toxic metals, in the root zone. Teng et al. (2018) reported that due to surface water and groundwater interactions, contaminants from groundwater can be transported, resulting in deterioration of surface water quality.

For sustainable economic development, balancing human demand with the renewal rate of natural resources is essential (Awan, 2013). Fresh groundwater is probably the most valuable natural resource. Yet, under chronic groundwater contamination, the freshwater supply can be depleted, breaking the balance of demand and water availability to the degree of socio-economic stress and even war. Water shortages as a result of contamination are likely to become a factor in a future conflict between locals (Ricart et al., 2021), ultimately delaying the socio-economic development of the community. The issue of groundwater contamination is not just an environmental issue; it is also a social issue, requiring close cooperation among social scientists and environmental scientists.

3. Groundwater Vulnerability Assessment Methods

3.1. The DRASTIC Approach to Mapping Groundwater Vulnerability

3.1.1. Theory

The DRASTIC method by the National Water Well Association (NWWA) and the United States Environmental Protection Agency (USEPA) was developed in 1987 to assist administrators, planners, and managers (Aller et al., 1987). The principle of vulnerability assessment by the DRASTIC method is based on three fundamental assumptions: the contaminant is considered to have the same mobility as water; the contaminant is carried from the soil surface to the aquifer by effective infiltration, i.e., by vertical flow; and the source of potential contamination is located at the soil surface.

The DRASTIC method assesses the intrinsic vertical vulnerability of aquifers to contamination by taking into account seven hydrogeological parameters. DRASTIC matches the first letters of the seven parameters: Depth to water (D); Net Recharge (R); Aquifer media (A); Soil media (S); Topography (T); Impact of the vadose zone (I); and Hydraulic Conductivity of the aquifer (C). First, the parameters are classified into ranges (for continuous variables) or classes (for thematic data) and then assigned a rating value (r) between 1 and 10, impacting the potential pollution. Second, weight multipliers (w), between 1 and 5, are assigned to each parameter to balance and reinforce their significance. The output is a vulnerability index (VI) that is a weighted sum of the rating value (r) multiplied by (w), the weight associated with each of the seven parameters: D, R, A, S, T, I, and C:

$$\mathrm{VI} = \mathrm{Dr} * \mathrm{Dw} + \mathrm{Rr} * \mathrm{Rw} + \mathrm{Ar} * \mathrm{Aw} + \mathrm{Sr} * \mathrm{Sw} + \mathrm{Tr} * \mathrm{Tw} + \mathrm{Ir} * \mathrm{Iw} + \mathrm{Cr} * \mathrm{Cw} \qquad (1)$$

(where D, R, A, S, T, I, and C are the seven parameters of the DRASTIC method, W being the weight of the parameter, and R the associated score or rate).

Two versions of the DRASTIC method exist: the standard DRASTIC version, applied in the case where the contaminants considered are inorganic pollutants, and the DRASTIC pesticide version, applied in the case where the contaminants considered are pesticides. The values of the ratings (r) and weights (W) of the parameters, in both versions of DRASTIC, are shown in **Table 2**. Calculated DRASTIC index values reflect the hydrogeological vulnerability of the aquifer, with specific zones recognized as being more sensitive than others to groundwater contamination. DRASTIC index values range from 23 to 226 for the standard version and from 26 to 256 for the pesticide version. These values are grouped into five classes, each corresponding to a degree of vulnerability: very high, high, medium, low, and very low (Aller et al., 1987) (**Table 3**). On the other hand, Engel et al. (1996) propose classifying values into four further classes (**Table 4**). According to Aller et al. (1987), the contaminant imitates the mobility of groundwater. Therefore, contaminants released at the surface are likely to reach groundwater. This approach focuses on man-made contamination rather than pollutants released at the surface or at depth by processes such as injection wells, animal waste lagoons, or leaking underground storage tanks.

Table 2. Parameter ratings and weights in standard and pesticide versions of DRASTIC based on Aller et al. (1987).

Parameter	Range	Rate	WeightStan.	WeightPest.
Depth to water (m)	>30	1	5	5
	23 - 30	2		
	15 - 23	3		
	9 - 15	5		
	4.5 - 9	7		
	1.5 - 4.5	9		
	0 - 1.5	10		
Net Recharge (mm)	0 - 50	1	4	4
	50 - 100	3		
	100 - 180	6		
	180 - 250	8		
	>250	9		
Aquifer media	Massive shale	2	3	3
	Metamorphic	3		
	Weathered metamorphic	4		
	Glacial	5		
	Bedded sandstones and limestones	6		
	Massive sandstone and limestone	7		
	Sand and gravel	8		
	Basalt	9		
	Karst limestone	10		
Soil media	Non-shrink and no-aggregate clay	1	2	5
	Muck acid, granitoid	2		
	Clay loam	3		
	Silty loam	4		
	Loam	5		
	Sandy loam, schist, sand, karst volcanic.	6		
	Shrinking/aggregate clay/alluvium	7		
	Peat	8		
	Sandstone and volcanic	9		
	Thin or absent gravel	10		

Continued

Topography (%)	> 18	1	1	3
	16 - 18	2		
	12 - 16	3		
	10 - 12	4		
	6 - 10	5		
	5 - 6	6		
	4 - 5	7		
	3 - 4	8		
	2 - 3	9		
	0 - 2	10		
Impact of the vadose zone	Confining layer, granite	1	5	4
	Silt clay	2		
	Shale, silt, and clay	3		
	Metamorphic gravel and sandstone	4		
	Sandy silt	5		
	Limestone, gravel, sand, clay	6		
	Gravel, sand	7		
	Sand and gravel	8		
	Basalt	9		
	Karst limestone	10		
Hydraulic Conductivity of the aquifer	1.5e−7–5e−5	1	3	2
	5e−5–15e−5	2		
	15e−5–33e−5	4		
	33e−5–5e−4	6		
	5e−4–9.5e−4	8		
	>6.5e−4	10		

Table 3. Vulnerability assessment criteria for standard and pesticide.

Class Vulnerability	Vulnerability index	
	DRASTIC-Standard	DRASTIC-Pesticide
Very high	>200	>200
High	161 - 200	141 - 200

Continued

Moderate	121 - 160	101 - 140
Low	80 - 120	< 101
Very low	<80	-

3.1.2. Advantages

DRASTIC model applications range from the local scale, with the study by Tomer et al. (2019) in the National Capital Territory of Delhi, India, to the continental scale, through a critical application of the DRASTIC method by Rama et al. (2022) to investigate South American groundwater.

An important benefit of the DRASTIC method resides in its flexibility to eliminate and integrate specific parameters into the model, depending on the availability of data and the conditions of the area under study (Ahmed et al., 2022; Singh et al., 2015; Thirumalaivasan et al., 2003). Moreover, rate and weight scores can be adjusted according to field measurement data.

Nevertheless, it has been indicated by Hamza et al. (2015) that groundwater contamination is influenced in the same way by all parameters, insofar as each parameter indicates a significant impact regardless of the weighting assigned to the parameters. Decision-makers and researchers, therefore, need to go beyond the assumed weight of a given factor when assessing groundwater vulnerability and to perform an in-depth scientific analysis if they are to manage groundwater contamination effectively.

The DRASTIC approach is a useful tool for groundwater vulnerability assessment due to its simplicity, the availability of widely estimated or widely available data, and its low cost. The DRASTIC approach is a useful tool for groundwater vulnerability assessment due to its simplicity, the availability of widely estimated or widely available data, and its low cost. The application of the Geographic Information System (GIS) allows us to produce a map that is easy to both understand and integrate into the decision-making process (Abunada et al., 2021).

3.1.3. Applications

As mentioned earlier, the DRASTIC method is one of the most widely used methods for assessing the vulnerability of groundwater resources, owing to its ease of application and performance. At present, there are two options for adapting the DRASTIC method to field conditions and improving the results obtained with the DRASTIC method:

The first option for improving DRASTIC's efficiency, based on an in-depth scientific analysis of the data, is to optimize the weighting and rating of the model's parameters. Some successful approaches have been experimented with in recent years. Single-parameter sensitivity analysis (SA-DRASTIC), fuzzy pattern recognition (F-DRASTIC), and entropy information (E-DRASTIC) were applied by Sahoo et al. (2016) to Kanpur City in India to more appropriately weight DRASTIC factors for vulnerability to groundwater contamination while comparing the performance of subjective (DRASTIC, SA-DRASTIC) and objective (F-DRASTIC, E-DRASTIC) models based on weighting. The results showed the effectiveness of objective methods in assessing the vulnerability of Kanpur City.

In the second option, DRASTIC's performance can be enhanced by altering its original parameters, whether by adding or substituting with other parameters, such as irrigation type and land use. A study was carried out in the Tiruchirappalli district (India), an area with extensive agricultural practices. To ensure a better assessment of the area's vulnerability, Jenifer and Jha (2018) used the original DRASTIC and DRASTIC-P models, to which two further parameters were added: lineament density (LD) and land use (LU). The two original models (DRASTIC and DRASTIC-P) were then compared with six modified versions of these models, namely DRASTIC-LU, DRASTIC-LD, DRASTIC-LULD, DRASTIC-P-LU, DRASTIC-P-LD, and DRASTIC-P-LULD. All eight vulnerability models were validated using a single water quality parameter (F^-, Cl^-, and NO_3^--N). With 61% and 68% accuracy for nitrate and chloride concentrations, respectively, the most accurate model was DRASTIC-P-LDLU, and the second most accurate model was DRASTIC-LDLU, with 59% and 61% accuracy for the same concentrations.

3.1.4. Limitations

The DRASTIC method for delineating vulnerable zones underestimates groundwater pollution potential (Bai et al., 2012). In the literature, the application of the DRASTIC method works for all potential contaminants, regardless of anthropogenic activities. Therefore, the complexity of a specific vulnerability assessment may lie in the wide diversity of pollutants present in nature, whose behavior and fate in hydrogeological units are highly disparate. As a result, there is a need for careful use of a simple system that guarantees the accuracy of results (Ferreira & Oliveira, 2004).

A further limitation of the DRASTIC method is that the data used to generate the various parameters applied by the approach influence the reliability of these parameters. In most cases, most information comes from interpolation (Barbulescu, 2020), as in the case of parameters conditioned by the lithology of the environment, such as hydraulic conductivity, effective aquifer recharge, the impact of the vadose zone, and water table depth (Kouz et al., 2020). This aspect leads to errors when generating parameter values, as it is only accurate within the intervals delimited by the punctual data. Consequently, the DRASTIC model can only be used as a relative assessment tool and not to provide an absolute assessment of groundwater vulnerability.

Moreover, another limitation of the DRASTIC approach is that it assumes that water and contaminants penetrate vertically from the ground surface to the water table. However, the method ignores the different situations in karst aquifers, where water and contaminants flow laterally through shallow holes (Oke, 2017).

3.2. SI Method

3.2.1. Theory

The Susceptibility Index (SI) is a model developed in Portugal by Ribeiro (2000) to assess specific vertical vulnerability to agricultural pollution (mainly nitrates but also pesticides). The model involves five parameters. One is land use (LU), and the other four are identical to four parameters already used in the DRASTIC method, namely depth to water (D), net recharge (R), aquifer media (A), and topography (T). The SI method omits three DRASTIC parameters: hydraulic conductivity, soil environment, and aquifer vadose zone. Indeed, the inclusion of the additional parameter (land use), according to Ribeiro (2000), in the SI method compared to the DRASTIC method is based on the fact that land use remains a key and influential factor in the contamination of groundwater by pollution generated by anthropogenic activities. As per Brindha and Elango (2015) and Teixeira et al. (2015), the integration of the land use factor in groundwater quality assessment is a key issue that should be taken into account when predicting the effect of anthropogenic activities on groundwater quality. In addition, Francés et al. (2001) consider the soil environment as a factor indirectly represented by land use, so its use remains a repetition. Further, the deletion of the vadose zone and hydraulic conductivity is justified by the fact that these two factors overlap (Stigter et al., 2006), and, besides that, hydraulic conductivity reflects the aquifer media already included (Engel et al., 1996).

The Susceptibility Index (SI) is computed by summing the products of the ratings and the corresponding parameter weights:

$$\mathrm{SI} = \mathrm{Dr} * \mathrm{Dw} + \mathrm{Rr} * \mathrm{Rw} + \mathrm{Ar} * \mathrm{Aw} + \mathrm{Tr} * \mathrm{Tw} + \mathrm{OSr} * \mathrm{OSw}_2 \tag{2}$$

(where D, R, A, T, and OS are the five parameters of the SI method, W being the weight of the parameter, and R the associated score or rate).

With the SI method, the ranges for water depth, net recharge, topography, and aquifer media are the same as in DRASTIC, whereas the ranges used for land use are derived from the Portuguese scientists' classification (EUROPEAN COMMUNITY, 1993), as depicted in **Table 4**.

Table 4. Main land use classes and corresponding rates.

Land use types	Rate
Industrial waste discharge, landfills, and mines	100
Paddy fields, irrigation perimeters (annual crops)	90
Open-air mines, quarries, shipyards	80
Continuous urban areas, airports, harbors, (rail)roads, areas with industrial or commercial activity, laid-out green space	75
Permanent crops (vineyards, orchards, olive groves, etc.)	70
Discontinuous urban areas	70

Continued

Aquatic environments (salt marshes, salinas, intertidal zones)	50
Heterogeneous agricultural areas	50
Pastures and agro-forested areas	50
Water bodies	0
Forests and semi-natural zones	0

The weights attributed to SI parameters, ranging from 0 to 1, are shown in **Table 5** in accordance with the parameters' importance in vulnerability.

Table 5. Weights allocated to SI parameters.

Parameter	D	R	A	T	LU
weight	0.186	0.212	0.259	0.121	0.222

Based on the index values obtained from equation (2), **Table 6** lists the four degrees of vulnerability of the SI method.

Table 6. Vulnerability categories for the SI method.

Class Vulnerability	Vulnerability index
Very high	85 - 100
High	65 - 84
Moderate	45 - 64
Low	<45

3.2.2. Advantages

Geographic Information Systems (GIS) and remote sensing technologies are increasingly being used in groundwater contamination risk assessment. These technologies, combined with the SI method, allow us to develop an integrated approach with an emphasis on heterogeneous environments that take into account geochemical, hydrological and geological data in order to improve the vulnerability assessment accuracy (Anane et al., 2013; Bartzas et al., 2015). Moreover, the SI approach, similar to the DRASTIC method, has been developed to assess the vulnerability of aquifers on a medium and large scale (e.g., 1: 200,000 - 1: 50,000).

3.2.3. Applications

Over the past few years, numerous aquifer vulnerability assessments have been carried out all over the world using the SI method. An application of the SI method by El Himer et al. (2013) to assess the vulnerability of the hydrogeological watershed of the Oualidia-Sidi Moussa wetland in Morocco reveals that the area is characterized by medium to high vulnerability to pollution. According to El Himer et al.

(2013), the high vulnerability to pollution reflects the nitrate levels measured in groundwater during sampling campaigns. The SI method's land-use parameter has proved useful in the Caldas da Cavaca area in Central Portugal, highlighting urban areas where agricultural land and buildings are concentrated (Teixeira et al., 2015). For Teixeira et al. (2015), most of the Caldas da Cavaca area has moderate and low-to-moderate vulnerability values, due to the presence of high slopes, rocky outcrops, and less weathered granitic zones. Recently, Ghouili et al. (2021) applied the SI method in the northeast of Tunisia to assess the vulnerability of the Takelsa phreatic aquifer to contamination. In order to validate the generated vulnerability maps, high-salinity groundwater areas were compared to their respective vulnerability indices. From these validated vulnerability maps, Ghouili et al. (2021) reported that these high-vulnerability areas can be associated with low slopes, sandy soils, shallow water tables, and highly agricultural areas with very high recharge rates.

3.2.4. Limitations

One of the weaknesses of the SI method is that it fails to identify the path that the contaminant will take through the hydrogeological system. Indeed, the SI method is limited to vertical movements, ignoring the lateral migration of elements. Therefore, the SI method deals with the water's sources of contamination rather than the state of pollution itself. Other SI method limitations include the need to correlate the vulnerability index with the nitrate concentration measured in the field in order to validate the method. Indeed, the use of the SI method on the shallow aquifer of Nabeul-Hammamet in Tunisia (Anane et al., 2013) and the southern aquifer of Teheran (Noori et al., 2019) revealed an overestimation of vulnerability due to the impact of dilution, highlighting the difference between the most vulnerable zones and the most contaminated zones. Moreover, Anane et al. (2013) reported that groundwater recycling, which contributes to the accumulation of pollutants, leads to an underestimation of vulnerability as two factors are not taken into account, namely the unsaturated zone and the soil conditions.

3.3. DRASTIC Model Compared to S.I. Model for Vulnerability Assessment

The basic principle of the DRASTIC and SI methods is the use of parameters within a weight-class system. However, the weights assigned to the different parameters by the two approaches differ. Therefore, the resulting intrinsic vulnerability also varies according to their inputs. To achieve greater confidence in the vulnerability assessment approach, the best strategy is to conduct case studies in areas where contamination has occurred. These studies ultimately make it possible to compare the results of different vulnerability assessment methods in terms of their consistency and relevance.

In the Nabeul-Hammamet shallow aquifer in Tunisia, Anane et al. (2013) tested the effectiveness of the DRASTIC, DRASTIC-Pesticide, and Susceptibility Index methods for determining the degree of vulnerability to pollution. According to Anane et al. (2013), there was a major difference between the vulnerability maps obtained using the DRASTIC and SI methods, as the DRASTIC and SI categories overlapped in only 27% of the total aquifer area, with SI reflecting field reality better than DRASTIC. The reason is that the SI method gives greater weight to the LU parameter than to the other four factors. Meanwhile, the Nabeul-Hammamet area is an agricultural zone and is, therefore, less likely to pollute groundwater. On the other hand, Anane et al. (2013) reported a good correlation between SI and Pesticide DRASTIC (64% of the total aquifer area). Such a match can be explained by the fact that both models assess the specific vulnerability to human activity, especially agriculture practiced in the Nabeul-Hammamet. Another factor is the high weight given to land use in the SI method and to soil media in the Pesticide DRASTIC method, as soil characteristics have a strong influence on land use. An assessment of groundwater vulnerability by Duarte et al. (2019) in Portugal's Serra da Estrela Mountains shows that SI vulnerability index values tend to be lower when compared with DRASTIC vulnerability index values, which tend to be more intermediate. This makes DRASTIC the most balanced choice for a strict display of intrinsic groundwater vulnerability. Conversely, the influence of specific agricultural and urban land use classes is only represented on the SI map. An application of the DRASTIC and SI methods to study vulnerability to potential nitrate pollution in the Timahdite-Almis Guigou groundwater in Morocco Amrani et al. (2019) revealed that the coincidence rate of groundwater nitrate concentrations with the different vulnerability classes established was 61.54% and 76.92%, respectively, for the DRASTIC and SI methods. From this rate of coincidence, the SI method appears to be the most appropriate for assessing vulnerability to nitrate pollution. In southern Portugal, Stigter et al. (2006) applied the DRASTIC and SI methods to nitrate contamination and groundwater salinization in two agricultural regions (Campina de Faro and Campina da Luz). In Campina da Luz, characterized by karstified limestone aquifers, both DRASTIC and SI methods overestimated vulnerability due to neglect of the dilution aspect. Despite having significant control over contamination levels, the DRASTIC method ignores groundwater dilution, thereby leading to inaccurate results (Alleret al., 1987). SI minimizes DRASTIC's error by eliminating the impact of the vadose zone. In fact, SI incorporates land use, which provides valuable additional information. Meanwhile, using the SI method tends to overestimate vulnerability, which is preferable to underestimation, since it involves the security of uncertainty (Elshall et al., 2020). A study by Brindha and Elango (2015) to identify the most appropriate method for assessing groundwater vulnerability in a weathered rock aquifer in southern India found that highly vulnerable areas to pollution in DRASTIC and Pesticide DRASTIC were similar to, but differed from, those identified by the SI method, which includes "land use" as one of the input parameters. The LU parameter, concludes Brindha and Elango (2015), is a crucial input that needs to be taken into account in any hydrogeological context.

4. Conclusions

This study presents a review of two methods, DRASTIC and SI, for assessing aquifer vulnerability with a view to safeguarding resources. Based on subjective weighting and the assessment of relevant parameters, the two approaches are suitable for porous aquifers. In addition, they have proven to be appropriate for karst and fractured/cracked aquifer systems, where groundwater flow is typical.

Assigning scores and weighting coefficients to each parameter in the DRASTIC and SI methods results in a lack of solid criteria for vulnerability classification and significant uncertainties. Thus, the water quality parameter can be used to validate vulnerability maps, which should be a mandatory step. To minimize erroneous decisions, it is essential to keep the objective of groundwater assessment as rigorous as possible.

Although there are similarities between the maps obtained using the DRASTIC and SI methods, these are far from self-evident. DRASTIC indicates only the potential for nitrate pollution to reach the water table, whereas SI gives a picture of the pollution phenomena likely to occur for a given land use. The maps provided by DRASTIC and SI are therefore not necessarily superimposable. However, combining the DRASTIC and SI methods has the advantage of ensuring a certain complementarity in the assessment of vulnerability to nitrate pollution. It would therefore be advisable to use both methods at the same time for vulnerability assessments.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

Abdel-Satar, A. M., Al-Khabbas, M. H., Alahmad, W. R., Yousef, W. M., Alsomadi, R. H., & Iqbal, T. (2017). Quality Assessment of Groundwater and Agricultural Soil in Hail Region, Saudi Arabia. *Egyptian Journal of Aquatic Research, 43,* 55-64. https://doi.org/10.1016/j.ejar.2016.12.004

Abunada, Z., Kishawi, Y., Alslaibi, T. M., Kaheil, N., & Mittelstet, A. (2021). The Application of SWAT-GIS Tool to Improve the Recharge Factor in the DRASTIC Framework: Case Study. *Journal of Hydrology, 592,* Article ID: 125613. https://doi.org/10.1016/j.jhydrol.2020.125613

Adetunji, V. O., & Odetokun, I. A. (2011). Groundwater Contamination in Agbowo Community, Ibadan Nigeria: Impact of Septic Tanks Distances to Wells. *Malaysian Journal of Microbiology, 7,* 159-166. https://doi.org/10.21161/mjm.33011

Adeyemi, A. A., & Ojekunle, Z. O. (2021). Concentrations and Health Risk Assessment of Industrial Heavy Metals Pollution in Groundwater in Ogun State, Nigeria. *Scientific African, 11,* e00666. https://doi.org/10.1016/j.sciaf.2020.e00666

Adimalla, N. (2019). Human and Ecological Risk Assessment: An International Spatial Distribution, Exposure, and Potential Health Risk Assessment from Nitrate in Drinking

Water from Semi-Arid Region of South India Assessment from Nitrate in Drinking Water from Semi-Arid. *Human and Ecological Risk Assessment*, **26**, 310-334. https://www.tandfonline.com/doi/abs/10.1080/10807039.2018.1508329

Adimalla, N., & Venkatayogi, S. (2018). Geochemical Characterization and Evaluation of Groundwater Suitability for Domestic and Agricultural Utility in Semi-Arid Region of Basara, Telangana State, South India. *Applied Water Science, 8,* 1-14. https://doi.org/10.1007/s13201-018-0682-1

Adimalla, N., Qian, H., & Nandan, M. J. (2020). Groundwater Chemistry Integrating the Pollution Index of Groundwater and Evaluation of Potential Human Health Risk: A Case Study from Hard Rock Terrain of South India. *Ecotoxicology and Environmental Safety, 206,* Article ID: 111217. https://doi.org/10.1016/j.ecoenv.2020.111217

Adimalla, N., Venkatayogi, S., & Das, S. V. G. (2019). Assessment of Fluoride Contamination and Distribution: A Case Study from a Rural Part of Andhra Pradesh, India. *Applied Water Science, 9,* 1-15. https://doi.org/10.1007/s13201-019-0968-y

Ahmad, A. Y., Al-Ghouti, M. A., Khraisheh, M., & Zouari, N. (2020). Hydrogeochemical Characterization and Quality Evaluation of Groundwater Suitability for Domestic and Agricultural Uses in the State of Qatar. *Groundwater for Sustainable Development, 11,* Article ID: 100467. https://doi.org/10.1016/j.gsd.2020.100467

Ahmed, A. T., & Askri, B. (2016). Seawater Intrusion Impacts on the Water Quality of the Groundwater on Thenorthwest Coast of Oman. *Water Environment Research, 88,* 732-740. https://doi.org/10.2175/106143016x14609975747045

Ahmed, K. M., Bhattacharya, P., Hasan, M. A., Akhter, S. H., Alam, S. M. M., Bhuyian, M. A. H. et al. (2004). Arsenic Enrichment in Groundwater of the Alluvial Aquifers in Bangladesh: An Overview. *Applied Geochemistry, 19,* 181-200. https://doi.org/10.1016/j.apgeochem.2003.09.006

Ahmed, N., Bodrud-Doza, M., Islam, S. M. D., Choudhry, M. A., Muhib, M. I., Zahid, A. et al. (2019). Hydrogeochemical Evaluation and Statistical Analysis of Groundwater of Sylhet, North-Eastern Bangladesh. *Acta Geochimica, 38,* 440-455. https://doi.org/10.1007/s11631-018-0303-6

Ahmed, S. I., Cheng, C., Gonzalez, J., Kang, J. J., Ho, J., & Soto-Sanchez, L. (2022). Groundwater Vulnerability Assessment of Shallow Aquifer in the South Texas Sand Sheet Using a GIS-Based DRASTIC Model. *Modeling Earth Systems and Environment, 8,* 4075-4091. https://doi.org/10.1007/s40808-021-01292-4

Akram, S., & Rehman, F. (2018). Hardness in Drinking-Water, Its Sources, Its Effects on Humans and Its Household Treatment. *Journal of Chemistry and Applications, 4,* 1-4.

Albinet, M., & Margat, J. (1970). Groundwater Pollution Vulnerability Mapping. *Bulletin Du Bureau de Researches Geologicques et Minieres 2nd Series, 3,* 13-22.

Alessa, L., Kliskey, A., Lammers, R., Arp, C., White, D., Hinzman, L. et al. (2008). The Arctic Water Resource Vulnerability Index: An Integrated Assessment Tool for Community Resilience and Vulnerability with Respect to Freshwater. *Environmental Management, 42,* 523-541. https://doi.org/10.1007/s00267-008-9152-0

Alfarrah, N., & Walraevens, K. (2018). Groundwater Overexploitation and Seawater Intrusion in Coastal Areas of Arid and Semi-Arid Regions. *Water, 10,* Article No. 143. https://doi.org/10.3390/w10020143

Ali, S., Thakur, S. K., Sarkar, A., & Shekhar, S. (2016). Worldwide Contamination of Water by Fluoride. *Environmental Chemistry Letters, 14,* 291-315. https://doi.org/10.1007/s10311-016-0563-5

Aller, L., Lehr, J. H., Petty, R., & Bennett, T. (1987). DRASTIC: A Standardized System to

Evaluate Groundwater Pollution Potential Using Hydrogeologic Setting. *Journal Geological Society of India, 29,* 23-37.

Almasri, M. N., & Kaluarachchi, J. J. (2004). Assessment and Management of Long-Term Nitrate Pollution of Ground Water in Agriculture-Dominated Watersheds. *Journal of Hydrology, 295,* 225-245. https://doi.org/10.1016/j.jhydrol.2004.03.013

AlSuhaimi, A. O., AlMohaimidi, K. M., & Momani, K. A. (2019). Preliminary Assessment for Physicochemical Quality Parameters of Groundwater in Oqdus Area, Saudi Arabia. *Journal of the Saudi Society of Agricultural Sciences, 18,* 22-31. https://doi.org/10.1016/j.jssas.2016.12.002

Ambast, S. K., Tyagi, N. K., & Raul, S. K. (2006). Management of Declining Groundwater in the Trans Indo-Gangetic Plain (India): Some Options. *Agricultural Water Management, 82,* 279-296. https://doi.org/10.1016/j.agwat.2005.06.005

Amrani, S., Hinaje, S., & Gharmane, Y. (2019). Application des méthodes paramétriques (drastic et si) pour l'étude de la vulnérabilité à la pollution potentielle par les nitrates de la nappe d'eau superficielle de Timahdite-Almis Guigou (Moyen Atlas, Maroc). *Revue des Sciences de l'Eau, 32,* 237-252. https://doi.org/10.7202/1067307ar

Anane, M., Abidi, B., Lachaal, F., Limam, A., & Jellali, S. (2013). GIS-Based DRASTIC, Pesticide DRASTIC and the Susceptibility Index (SI): Comparative Study for Evaluation of Pollution Potential in the Nabeul-Hammamet Shallow Aquifer, Tunisia. *Hydrogeology Journal, 21,* 715-731. https://doi.org/10.1007/s10040-013-0952-9

APVMA (2008). *Atrazine Review-Final Review Report & Regulatory Decision Volume Australian Pesticides & Veterinary Medicines Authority* (pp. 1-34). Scopus.

Awan, A. G. (2013). Relationship between Environment and Sustainable Economic Development: A Theoretical Approach to Environmental Problems. *International Journal of Asian Social Science, 3,* 741-761.

Ayotte, J. D., Belaval, M., Olson, S. A., Burow, K. R., Flanagan, S. M., Hinkle, S. R. et al. (2015). Factors Affecting Temporal Variability of Arsenic in Groundwater Used for Drinking Water Supply in the United States. *Science of the Total Environment, 505,* 1370-1379. https://doi.org/10.1016/j.scitotenv.2014.02.057

Badeenezhad, A., Tabatabaee, H. R., Nikbakht, H., Radfard, M., Abbasnia, A., Baghapour, M. A. et al. (2020). Estimation of the Groundwater Quality Index and Investigation of the Affecting Factors Their Changes in Shiraz Drinking Groundwater, Iran. *Groundwater for Sustainable Development, 11,* Article ID: 100435. https://doi.org/10.1016/j.gsd.2020.100435

Bahir, M., Ouhamdouch, S., Ouazar, D., & El Moçayd, N. (2020). Climate Change Effect on Groundwater Characteristics within Semi-Arid Zones from Western Morocco. *Groundwater for Sustainable Development, 11,* Article ID: 100380. https://doi.org/10.1016/j.gsd.2020.100380

Bai, L., Wang, Y., & Meng, F. (2012). Application of Drastic and Extension Theory in the Groundwater Vulnerability Evaluation. *Water and Environment Journal, 26,* 381-391. https://doi.org/10.1111/j.1747-6593.2011.00298.x

Balasooriya, S., Munasinghe, H., Herath, A. T., Diyabalanage, S., Ileperuma, O. A., Manthrithilake, H. et al. (2020). Possible Links between Groundwater Geochemistry and Chronic Kidney Disease of Unknown Etiology (CKDU): An Investigation from the Ginnoruwa Region in Sri Lanka. *Exposure and Health, 12,* 823-834. https://doi.org/10.1007/s12403-019-00340-w

Barbulescu, A. (2020). Assessing Groundwater Vulnerability: DRASTIC and Drastic-Like Methods: A Review. *Water, 12,* Article No. 1356. https://doi.org/10.3390/w12051356

Barlow, P. M., & Reichard, E. G. (2010). Saltwater Intrusion in Coastal Regions of North

America. *Hydrogeology Journal, 18,* 247-260. https://doi.org/10.1007/s10040-009-0514-3

Bartzas, G., Tinivella, F., Medini, L., Zaharaki, D., & Komnitsas, K. (2015). Assessment of Groundwater Contamination Risk in an Agricultural Area in North Italy. *Information Processing in Agriculture, 2,* 109-129. https://doi.org/10.1016/j.inpa.2015.06.004

Bougherira, N., Hani, A., Djabri, L., Toumi, F., Chaffai, H., Haied, N. et al. (2014). Impact of the Urban and Industrial Waste Water on Surface and Groundwater, in the Region of Annaba, (Algeria). *Energy Procedia, 50,* 692-701. https://doi.org/10.1016/j.egypro.2014.06.085

Brindha, K., & Elango, L. (2015). Cross Comparison of Five Popular Groundwater Pollution Vulnerability Index Approaches. *Journal of Hydrology, 524,* 597-613. https://doi.org/10.1016/j.jhydrol.2015.03.003

Burns, D., Vitvar, T., McDonnell, J., Hassett, J., Duncan, J., & Kendall, C. (2005). Effects of Suburban Development on Runoff Generation in the Croton River Basin, New York, Usa. *Journal of Hydrology, 311,* 266-281. https://doi.org/10.1016/j.jhydrol.2005.01.022

Civita, M. (1994). *Aquifer Vulnerability Maps to Pollution*. Pitagora Ed.

Civita, M., & De Maio, M. (1997). *SINTACS: Un sistema parametrico per la valutazione e la cartografia delle vulnerabilità degli acquiferi all'inquinamento. Metodologia e automatizzazione* (Vol. 60). Pitagora Editrice.

Cobbina, S. J., Nyame, F. K., & Obiri, S. (2012). Groundwater Quality in the Sahelian Region of Northern Ghana, West Africa. *Research Journal of Environmental and Earth Sciences, 4,* 482-491.

Corniello, A., Ducci, D., & Ruggieri, G. (2007). Areal Identification of Groundwater Nitrate Contamination Sources in Periurban Areas. *Journal of Soils and Sediments, 7,* 159-166. https://doi.org/10.1065/jss2007.03.213

Costa, A. M., Alfaia, R. G. d. S. M., & Campos, J. C. (2019). Landfill Leachate Treatment in Brazil—An Overview. *Journal of Environmental Management, 232,* 110-116. https://doi.org/10.1016/j.jenvman.2018.11.006

Cushing, E. M., Kantrowitz, I. H., & Taylor, K. R. (1973). *Water Resources of the Delmarva Peninsula*. US Govt. Print. Off.

Czerewko, M. A., Cripps, J. C., Reid, J. M., & Duffell, C. G. (2003). Sulfur Species in Geological Materials—Sources and Quantification. *Cement and Concrete Composites, 25,* 657-671. https://doi.org/10.1016/s0958-9465(02)00066-5

Dippong, T., Mihali, C., Hoaghia, M., Cical, E., & Cosma, A. (2019). Chemical Modeling of Groundwater Quality in the Aquifer of Seini Town—Someş Plain, Northwestern Romania. *Ecotoxicology and Environmental Safety, 168,* 88-101. https://doi.org/10.1016/j.ecoenv.2018.10.030

Duarte, L., Espinha Marques, J., & Teodoro, A. C. (2019). An Open Source GIS-Based Application for the Assessment of Groundwater Vulnerability to Pollution. *Environments, 6,* Article No. 86. https://doi.org/10.3390/environments6070086

Duijvenbooden, W., & Waegeningh, H. (1987). *Vulnerability of Soil and Groundwater to Pollutants: International Conference Noordwijk ann Zee, The Netherlands, March 30-April 3, 1987* (pp. 2-5). TNO Committee on Hydrological Research.

Eary, J. F., Appelbaum, F. L., Durack, L., & Brown, P. (1989). Preliminary Validation of the Opposing View Method for Quantitative Gamma Camera Imaging. *Medical Physics, 16,* 382-387. https://doi.org/10.1002/j.2473-4209.1989.tb36308.x

Egbueri, J. C. (2019). Evaluation and Characterization of the Groundwater Quality and Hydrogeochemistry of Ogbaru Farming District in Southeastern Nigeria. *SN Applied*

Sciences, 1, 851. https://doi.org/10.1007/s42452-019-0853-1

El gawad, E. A., Lotfy, M. M., Sadooni, F. N., & Katheery, B. E. L. (2008). Assessment of the Oil Pollution Extent in the Offshore Sediments, Abu Dhabi, UAE. *Australian Journal of Basic and Applied Sciences, 2,* 561-574.

El Himer, H., Fakir, Y., Stigter, T. Y., Lepage, M., El Mandour, A., & Ribeiro, L. (2013). Assessment of Groundwater Vulnerability to Pollution of a Wetland Watershed: The Case Study of the Oualidia-Sidi Moussa Wetland, Morocco. *Aquatic Ecosystem Health & Management, 16,* 205-215. https://doi.org/10.1080/14634988.2013.788427

El-Naqa, A., & Al-Shayeb, A. (2009). Groundwater Protection and Management Strategy in Jordan. *Water Resources Management, 23,* 2379-2394. https://doi.org/10.1007/s11269-008-9386-x

El-Rawy, M., Ismail, E., & Abdalla, O. (2019). Assessment of Groundwater Quality Using GIS, Hydrogeochemistry, and Factor Statistical Analysis in Qena Governorate, Egypt. *Desalination and Water Treatment, 162,* 14-29. https://doi.org/10.5004/dwt.2019.24423

Elshall, A. S., Arik, A. D., El-Kadi, A. I., Pierce, S., Ye, M., Burnett, K. M. et al. (2020). Groundwater Sustainability: A Review of the Interactions between Science and Policy. *Environmental Research Letters, 15,* Article ID: 093004. https://doi.org/10.1088/1748-9326/ab8e8c

Elumalai, V., Nethononda, V. G., Manivannan, V., Rajmohan, N., Li, P., & Elango, L. (2020). Groundwater Quality Assessment and Application of Multivariate Statistical Analysis in Luvuvhu Catchment, Limpopo, South Africa. *Journal of African Earth Sciences, 171,* Article ID: 103967. https://doi.org/10.1016/j.jafrearsci.2020.103967

Engel, B., Navulur, K., Cooper, B., & Hahn, L. (1996). *Estimating Groundwater Vulnerability to Nonpoint Source Pollution from Nitrates and Pesticides on a Regional Scale.*

European Community (1993). *Corine Land Cover. Guide Technique* (144 p.). Office for Official Publications of the Communities, Environment, Nuclear Safety and Nuclear Safety and Civil Protection.

Francés, A., Paralta, E., Fernandes, J., & Ribeiro, L. (2001). Development and Application in the Alentejo Region of a Method to Assess the Vulnerability of Groundwater to Diffuse Agricultural Pollution: The Susceptibility Index. In *3rd International Conference on Future Groundwater Resources at Risk* (pp. 35-44). CVRM.

Gad, M. I., & Khalaf, S. (2015). Management of Groundwater Resources in Arid Areas Case Study: North Sinai, Egypt. *Water Resources, 42,* 535-552. https://doi.org/10.1134/s0097807815040053

Galliari, J., Santucci, L., Misseri, L., Carol, E., & Alvarez, M. d. P. (2021). Processes Controlling Groundwater Salinity in Coastal Wetlands of the Southern Edge of South America. *Science of the Total Environment, 754,* Article ID: 141951. https://doi.org/10.1016/j.scitotenv.2020.141951

Gardea-Torresdey, J. L., Peralta-Videa, J. R., De La Rosa, G., & Parsons, J. G. (2005). Phytoremediation of Heavy Metals and Study of the Metal Coordination by X-Ray Absorption Spectroscopy. *Coordination Chemistry Reviews, 249,* 1797-1810. https://doi.org/10.1016/j.ccr.2005.01.001

Garnier, F. (2012). *Contribution à l'évaluation biogéochimique des impacts liés à l'exploitation géothermique des aquifères superficiels: Expérimentations et simulations à l'échelle d'un pilote et d'installations réelles.* Université d'orléans.

Ghalib, H. B. (2017). Groundwater Chemistry Evaluation for Drinking and Irrigation Utilities in East Wasit Province, Central Iraq. *Applied Water Science, 7,* 3447-3467. https://doi.org/10.1007/s13201-017-0575-8

Ghazaryan, K., Movsesyan, H., Gevorgyan, A., Minkina, T., Sushkova, S., Rajput, V. et al. (2020). Comparative Hydrochemical Assessment of Groundwater Quality from Different Aquifers for Irrigation Purposes Using IWQI: A Case-Study from Masis Province in Armenia. *Groundwater for Sustainable Development, 11,* Article ID: 100459. https://doi.org/10.1016/j.gsd.2020.100459

Ghouili, N., Jarraya-Horriche, F., Hamzaoui-Azaza, F., Zaghrarni, M. F., Ribeiro, L., & Zammouri, M. (2021). Groundwater Vulnerability Mapping Using the Susceptibility Index (SI) Method: Case Study of Takelsa Aquifer, Northeastern Tunisia. *Journal of African Earth Sciences, 173,* Article ID: 104035. https://doi.org/10.1016/j.jafrearsci.2020.104035

Giddings, J. M. (2005). *Atrazine in North American Surface Waters: A Probabilistic Aquatic Ecological Risk Assessment.* SETAC.

Gueddari, H., Akodad, M., Baghour, M., Moumen, A., Skalli, A., Yousfi, Y. E. et al. (2022). The Salinity Origin and Hydrogeochemical Evolution of Groundwater in the Oued Kert Basin, North-Eastern of Morocco. *Scientific African, 16,* e01226. https://doi.org/10.1016/j.sciaf.2022.e01226

Halim, M. A., Majumder, R. K., Nessa, S. A., Hiroshiro, Y., Sasaki, K., Saha, B. B. et al. (2010). Evaluation of Processes Controlling the Geochemical Constituents in Deep Groundwater in Bangladesh: Spatial Variability on Arsenic and Boron Enrichment. *Journal of Hazardous Materials, 180,* 50-62. https://doi.org/10.1016/j.jhazmat.2010.01.008

Hamza, S. M., Ahsan, A., Imteaz, M. A., Rahman, A., Mohammad, T. A., & Ghazali, A. H. (2015). Accomplishment and Subjectivity of GIS-Based DRASTIC Groundwater Vulnerability Assessment Method: A Review. *Environmental Earth Sciences, 73,* 3063-3076. https://doi.org/10.1007/s12665-014-3601-2

Harvey, C. F., Swartz, C. H., Badruzzaman, A. B. M., Keon-Blute, N., Yu, W., Ali, M. A. et al. (2002). Arsenic Mobility and Groundwater Extraction in Bangladesh. *Science, 298,* 1602-1606. https://doi.org/10.1126/science.1076978

Hernández-Mena, L., Panduro-Rivera, M. G., Díaz-Torres, J. d. J., Ojeda-Castillo, V., Real-Olvera, J. d., López-Cervantes, M. et al. (2021). GIS, Multivariate Statistics Analysis and Health Risk Assessment of Water Supply Quality for Human Use in Central Mexico. *Water, 13,* Article No. 2196. https://doi.org/10.3390/w13162196

Inim, I. J., Udosen, N. I., Tijani, M. N., Affiah, U. E., & George, N. J. (2020). Time-Lapse Electrical Resistivity Investigation of Seawater Intrusion in Coastal Aquifer of Ibeno, Southeastern Nigeria. *Applied Water Science, 10,* 1-12. https://doi.org/10.1007/s13201-020-01316-x

Ismail, A. H., Hassan, G., & Sarhan, A. (2020). Hydrochemistry of Shallow Groundwater and Its Assessment for Drinking and Irrigation Purposes in Tarmiah District, Baghdad Governorate, Iraq. *Groundwater for Sustainable Development, 10,* Article ID: 100300. https://doi.org/10.1016/j.gsd.2019.100300

Ismail, A. H., Shareef, M. A., & Mahmood, W. (2018). Hydrochemical Characterization of Groundwater in Balad District, Salah Al-Din Governorate, Iraq. *Journal of Groundwater Science and Engineering, 6,* 306-322.

Jenifer, M. A., & Jha, M. K. (2018). Comparative Evaluation of GIS-Based Models for Mapping Aquifer Vulnerability in Hard-Rock Terrains. *Environmental Earth Sciences, 77,* 1-26. https://doi.org/10.1007/s12665-018-7821-8

Kadam, A., Wagh, V., Patil, S., Umrikar, B., & Sankhua, R. (2021). Seasonal Assessment of Groundwater Contamination, Health Risk and Chemometric Investigation for a Hard Rock Terrain of Western India. *Environmental Earth Sciences, 80,* 1-22. https://doi.org/10.1007/s12665-021-09414-y

Kaliraj, S., Chandrasekar, N., Peter, T. S., Selvakumar, S., & Magesh, N. S. (2015). Mapping of Coastal Aquifer Vulnerable Zone in the South West Coast of Kanyakumari, South India, Using GIS-Based DRASTIC Model. *Environmental Monitoring and Assessment, 187,* 1-27. https://doi.org/10.1007/s10661-014-4073-2

Kamal, Z. A., Sulaiman, M. S., Hakim, M. K., Thilageswaran,, Syahira, A., Hamzah, Z. et al. (2020). Investigation of Seawater Intrusion in Coastal Aquifers of Kelantan, Malaysia Using Geophysical and Hydrochemical Techniques. *IOP Conference Series: Earth and Environmental Science, 549,* Article ID: 012018. https://doi.org/10.1088/1755-1315/549/1/012018

Kathijotes, N., & Panayiotou, C. (2013). Wastewater Reuse for Irrigation and Seawater Intrusion: Evaluation of Salinity Effects on Soils in Cyprus. *Journal of Water Reuse and Desalination, 3,* 392-401. https://doi.org/10.2166/wrd.2013.072

Katyal, D., Tapasya, T., & Varun, J. (2017). Recent Trends in Groundwater Vulnerability Assessment Techniques: A Review. *International Journal of Applied Research, 3,* 646-655.

Katz, B. G., Eberts, S. M., & Kauffman, L. J. (2011). Using Cl/Br Ratios and Other Indicators to Assess Potential Impacts on Groundwater Quality from Septic Systems: A Review and Examples from Principal Aquifers in the United States. *Journal of Hydrology, 397,* 151-166. https://doi.org/10.1016/j.jhydrol.2010.11.017

Kaushik, A., Kumar, K., & Sharma, H. R. (2002). Water Quality Index and Suitability Assessment of Urban Ground Water of Hisar and Panipat in Haryana. *Journal of Environmental Biology, 23,* 325-333.

Kazi, T. G., Arain, M. B., Jamali, M. K., Jalbani, N., Afridi, H. I., Sarfraz, R. A. et al. (2009). Assessment of Water Quality of Polluted Lake Using Multivariate Statistical Techniques: A Case Study. *Ecotoxicology and Environmental Safety, 72,* 301-309. https://doi.org/10.1016/j.ecoenv.2008.02.024

Khan, N. I., Owens, G., Bruce, D., & Naidu, R. (2009). Human Arsenic Exposure and Risk Assessment at the Landscape Level: A Review. *Environmental Geochemistry and Health, 31,* 143-166. https://doi.org/10.1007/s10653-008-9240-3

Kouadra, R., & Demdoum, A. (2020). Hydrogeochemical Characteristics of Groundwater and Quality Assessment for the Purposes of Drinking and Irrigation in Bougaa Area, Northeastern Algeria. *Acta Geochimica, 39,* 642-654. https://doi.org/10.1007/s11631-019-00393-3

Kouz, T., Mansour, S., Mesmoudi, H., Dakak, H., & Cherkaoui Dekkaki, H. (2020). Assessment of Groundwater Vulnerability to Pollution as Part of Integrated Management in Coastal Areas Case of Ghiss-Nekkour Basin (North East of Morocco). *La Houille Blanche, 106,* 63-73. https://doi.org/10.1051/lhb/2020019

Kumar, P., Dipti, Kumar, S., & Singh, R. P. (2022). Severe Contamination of Carcinogenic Heavy Metals and Metalloid in Agroecosystems and Their Associated Health Risk Assessment. *Environmental Pollution, 301,* Article ID: 118953. https://doi.org/10.1016/j.envpol.2022.118953

Kumar, S. K., Rammohan, V., Sahayam, J. D., & Jeevanandam, M. (2009). Assessment of Groundwater Quality and Hydrogeochemistry of Manimuktha River Basin, Tamil Nadu, India. *Environmental Monitoring and Assessment, 159,* 341-351. https://doi.org/10.1007/s10661-008-0633-7

Kumar, S., Venkatesh, A. S., Singh, R., Udayabhanu, G., & Saha, D. (2018). Geochemical Signatures and Isotopic Systematics Constraining Dynamics of Fluoride Contamination in Groundwater across Jamui District, Indo-Gangetic Alluvial Plains, India. *Chemosphere, 205,* 493-505. https://doi.org/10.1016/j.chemosphere.2018.04.116

Kumari, M., & Rai, S. C. (2020). Hydrogeochemical Evaluation of Groundwater Quality for Drinking and Irrigation Purposes Using Water Quality Index in Semi-Arid Region of India. *Journal of the Geological Society of India, 95,* 159-168. https://doi.org/10.1007/s12594-020-1405-4

Li, P. (2014). *Research on Groundwater Environment under Human Interferences: A Case Study from Weining Plain, Northwest China*. Doctoral Thesis, Changan University.

Li, P., He, X., Li, Y., & Xiang, G. (2019). Occurrence and Health Implication of Fluoride in Groundwater of Loess Aquifer in the Chinese Loess Plateau: A Case Study of Tongchuan, Northwest China. *Exposure and Health, 11,* 95-107. https://doi.org/10.1007/s12403-018-0278-x

Li, P., Qian, H., Howard, K. W. F., & Wu, J. (2015). Building a New and Sustainable "Silk Road Economic Belt". *Environmental Earth Sciences, 74,* 7267-7270. https://doi.org/10.1007/s12665-015-4739-2

Lin, S. H., & Chang, C. C. (2000). Treatment of Landfill Leachate by Combined Electro-Fenton Oxidation and Sequencing Batch Reactor Method. *Water Research, 34,* 4243-4249. https://doi.org/10.1016/s0043-1354(00)00185-8

Lobo Ferreira, J. P., & Oliveira, M. M. (2004). Groundwater Vulnerability Assessment in Portugal. *Geofísica Internacional, 43,* 541-550. https://doi.org/10.22201/igeof.00167169p.2004.43.4.783

Loh, Y. S. A., Akurugu, B. A., Manu, E., & Aliou, A. (2020). Assessment of Groundwater Quality and the Main Controls on Its Hydrochemistry in Some Voltaian and Basement Aquifers, Northern Ghana. *Groundwater for Sustainable Development, 10,* Article ID: 100296. https://doi.org/10.1016/j.gsd.2019.100296

Lorette, G., Viennet, D., Labat, D., Massei, N., Fournier, M., Sebilo, M. et al. (2021). Mixing Processes of Autogenic and Allogenic Waters in a Large Karst Aquifer on the Edge of a Sedimentary Basin (Causses Du Quercy, France). *Journal of Hydrology, 593,* Article ID: 125859. https://doi.org/10.1016/j.jhydrol.2020.125859

Lu, Y., Tang, C., Chen, J., & Sakura, Y. (2008). Impact of Septic Tank Systems on Local Groundwater Quality and Water Supply in the Pearl River Delta, China: Case Study. *Hydrological Processes, 22,* 443-450. https://doi.org/10.1002/hyp.6617

Mahvi, A. H., Nouri, J., Babaei, A. A., & Nabizadeh, R. (2005). Agricultural Activities Impact on Groundwater Nitrate Pollution. *International Journal of Environmental Science & Technology, 2,* 41-47. https://doi.org/10.1007/bf03325856

Majeed, O. S., & Nashaat, M. R. (2022). Physicochemical Parameters of River Water and Their Relation to Zooplankton: A Review. *IOP Conference Series: Earth and Environmental Science, 1120,* Article 012040. https://doi.org/10.1088/1755-1315/1120/1/012040

Malik, A., Alam, I., Faridi, M. R., & Ayub, S. (2019). Corporate Social Irresponsibility towards the Planet: A Study of Heavy Metals Contamination in Groundwater Due to Industrial Wastewater. *Social Responsibility Journal, 16,* 793-807. https://doi.org/10.1108/srj-10-2018-0252

Mallick, J., Singh, C. K., AlMesfer, M. K., Kumar, A., Khan, R. A., Islam, S. et al. (2018). Hydro-Geochemical Assessment of Groundwater Quality in Aseer Region, Saudi Arabia. *Water, 10,* Article No. 1847. https://doi.org/10.3390/w10121847

Manecki, P., & Gałuszka, A. (2012). Groundwater Quality as a Geoindicator of Organochlorine Pesticide Contamination after Pesticide Tomb Reclamation: A Case Study of Franciszkowo, Northwestern Poland. *Environmental Earth Sciences, 67,* 2441-2447. https://doi.org/10.1007/s12665-012-1694-z

Marghade, D. (2020). Detailed Geochemical Assessment & Indexing of Shallow Groundwater Resources in Metropolitan City of Nagpur (Western Maharashtra, India) with Potential Health Risk Assessment of Nitrate Enriched Groundwater for Sustainable Development. *Geochemistry, 80,* Article ID: 125627. https://doi.org/10.1016/j.chemer.2020.125627

Masetti, M., Sterlacchini, S., Ballabio, C., Sorichetta, A., & Poli, S. (2009). Influence of Threshold Value in the Use of Statistical Methods for Groundwater Vulnerability Assessment. *Science of the Total Environment, 407,* 3836-3846. https://doi.org/10.1016/j.scitotenv.2009.01.055

Massoudinejad, M., Keramati, H., & Ghaderpoori, M. (2020). Investigation of Photo-Catalytic Removal of Arsenic from Aqueous Solutions Using UV/H_2O_2 in the Presence of ZnO Nanoparticles. *Chemical Engineering Communications, 207,* 1605-1615. https://doi.org/10.1080/00986445.2019.1674813

McCallum, J. L., Crosbie, R. S., Walker, G. R., & Dawes, W. R. (2010). Impacts of Climate Change on Groundwater in Australia: A Sensitivity Analysis of Recharge. *Hydrogeology Journal, 18,* 1625-1638. https://doi.org/10.1007/s10040-010-0624-y

Meybeck, M. (1987). Global Chemical Weathering of Surficial Rocks Estimated from River Dissolved Loads. *American Journal of Science, 287,* 401-428. https://doi.org/10.2475/ajs.287.5.401

Minhas, P. S., Saha, J. K., Dotaniya, M. L., Sarkar, A., & Saha, M. (2022). Wastewater Irrigation in India: Current Status, Impacts and Response Options. *Science of the Total Environment, 808,* Article ID: 152001. https://doi.org/10.1016/j.scitotenv.2021.152001

Mohammadpour, A., Gharehchahi, E., Badeenezhad, A., Parseh, I., Khaksefidi, R., Golaki, M. et al. (2022). Nitrate in Groundwater Resources of Hormozgan Province, Southern Iran: Concentration Estimation, Distribution and Probabilistic Health Risk Assessment Using Monte Carlo Simulation. *Water, 14,* Article No. 564. https://doi.org/10.3390/w14040564

Mostafa, M. G., Uddin, S. M. H., & Haque, A. B. M. H. (2017). Assessment of Hydro-Geochemistry and Groundwater Quality of Rajshahi City in Bangladesh. *Applied Water Science, 7,* 4663-4671. https://doi.org/10.1007/s13201-017-0629-y

Mtoni, Y., Mjemah, I. C., Bakundukize, C., Van Camp, M., Martens, K., & Walraevens, K. (2013). Saltwater Intrusion and Nitrate Pollution in the Coastal Aquifer of Dar Es Salaam, Tanzania. *Environmental Earth Sciences, 70,* 1091-1111. https://doi.org/10.1007/s12665-012-2197-7

Nefzaoui, F., Ben Hamouda, M. F., Carreira, P. M., Marques, J. M., & Eggenkamp, H. G. M. (2023). Evidence for Groundwater Salinity Origin Based on Hydrogeochemical and Isotopic (2H, 18O, 37Cl, 3H, 13C, 14C) Approaches: Sousse, Eastern Tunisia. *Water, 15,* Article No. 1242. https://doi.org/10.3390/w15061242

Nel, J., Xu, Y., Batelaan, O., & Brendonck, L. (2009). Benefit and Implementation of Groundwater Protection Zoning in South Africa. *Water Resources Management, 23,* 2895-2911. https://doi.org/10.1007/s11269-009-9415-4

Noori, R., Ghahremanzadeh, H., Kløve, B., Adamowski, J. F., & Baghvand, A. (2019). Modified-Drastic, Modified-Sintacs and SI Methods for Groundwater Vulnerability Assessment in the Southern Tehran Aquifer. *Journal of Environmental Science and Health, Part A, 54,* 89-100. https://doi.org/10.1080/10934529.2018.1537728

Nyanganji, J. K., Abdullahi, J., & Noma, I. U. S. (2011). Groundwater Quality and Related Water Borne Diseases in Dass Town, Bauchi State, Nigeria. *Journal of Environmental Issues and Agriculture in Developing Countries, 3,* 133-148.

Oke, S. A. (2017). *An Overview of Aquifer Vulnerability.*

Papazotos, P., Koumantakis, I., & Vasileiou, E. (2019). Hydrogeochemical Assessment and

Suitability of Groundwater in a Typical Mediterranean Coastal Area: A Case Study of the Marathon Basin, NE Attica, Greece. *HydroResearch, 2,* 49-59. https://doi.org/10.1016/j.hydres.2019.11.002

Pastén-Zapata, E., Ledesma-Ruiz, R., Harter, T., Ramírez, A. I., & Mahlknecht, J. (2014). Assessment of Sources and Fate of Nitrate in Shallow Groundwater of an Agricultural Area by Using a Multi-Tracer Approach. *Science of the Total Environment, 470,* 855-864. https://doi.org/10.1016/j.scitotenv.2013.10.043

Paydar, M., Mohammadi, A. A., & Zarei, A. (2020). Heavy Metals Exposure, Carcinogenic and Non-Carcinogenic Human Health Risks Assessment of Groundwater around Mines in Joghatai, Iran. *International Journal of Environmental Analytical Chemistry, 102,* 1-16.

Pratap, B., Kumar, S., Purchase, D., Bharagava, R. N., & Dutta, V. (2021). Practice of Wastewater Irrigation and Its Impacts on Human Health and Environment: A State of the Art. *International Journal of Environmental Science and Technology, 20,* 2181-2196.

Qureshi, A. L., Lashari, B. K., Kori, S. M., & Lashari, G. A. (2011). Hydro-Salinity Behavior of Shallow Groundwater Aquifer Underlain by Salty Groundwater in Sindh Pakistan. In *Proceedings, Fifteenth International Water Technology Conference* (pp. 1-15). International Water Technology Association (IWTA).

Racoviteanu, G. (2016). Evaluation of the Groundwater Quality in Constanta County, Seaside Area. *Energy Procedia, 85,* 612-619. https://doi.org/10.1016/j.egypro.2015.12.251

Rama, F., Busico, G., Arumi, J. L., Kazakis, N., Colombani, N., Marfella, L. et al. (2022). Assessment of Intrinsic Aquifer Vulnerability at Continental Scale through a Critical Application of the Drastic Framework: The Case of South America. *Science of the Total Environment, 823,* Article ID: 153748. https://doi.org/10.1016/j.scitotenv.2022.153748

Rattray, G. (2015). Geochemical Evolution of Groundwater in the Mud Lake Area, Eastern Idaho, USA. *Environmental Earth Sciences, 73,* 8251-8269. https://doi.org/10.1007/s12665-014-3988-9

Ren, X., Li, P., He, X., Su, F., & Elumalai, V. (2021). Hydrogeochemical Processes Affecting Groundwater Chemistry in the Central Part of the Guanzhong Basin, China. *Archives of Environmental Contamination and Toxicology, 80,* 74-91. https://doi.org/10.1007/s00244-020-00772-5

Ribeiro, L. (2000). *Desenvolvimento de um índice para avaliar a susceptibilidade dos aquíferos à contaminação.* Nota Interna, (Não Publicada), ERSHA-CVRM, 8.

Ricart, S., Villar-Navascués, R. A., Hernández-Hernández, M., Rico-Amorós, A. M., Olcina-Cantos, J., & Moltó-Mantero, E. (2021). Extending Natural Limits to Address Water Scarcity? The Role of Non-Conventional Water Fluxes in Climate Change Adaptation Capacity: A Review. *Sustainability, 13,* Article No. 2473. https://doi.org/10.3390/su13052473

Saalidong, B. M., Aram, S. A., Otu, S., & Lartey, P. O. (2022). Examining the Dynamics of the Relationship between Water pH and Other Water Quality Parameters in Ground and Surface Water Systems. *PLOS ONE, 17,* e0262117. https://doi.org/10.1371/journal.pone.0262117

Saana, S. B. B. M., Fosu, S. A., Sebiawu, G. E., Jackson, N., & Karikari, T. (2016). Assessment of the Quality of Groundwater for Drinking Purposes in the Upper West and Northern Regions of Ghana. *SpringerPlus, 5,* 2001. https://doi.org/10.1186/s40064-016-3676-1

Sahoo, M., Sahoo, S., Dhar, A., & Pradhan, B. (2016). Effectiveness Evaluation of Objective and Subjective Weighting Methods for Aquifer Vulnerability Assessment in Urban Context. *Journal of Hydrology, 541,* 1303-1315. https://doi.org/10.1016/j.jhydrol.2016.08.035

Saida, S., Tarik, H., Abdellah, A., Farid, H., & Hakim, B. (2017). Assessment of Groundwater Vulnerability to Nitrate Based on the Optimised DRASTIC Models in the GIS Environment (Case of Sidi Rached Basin, Algeria). *Geosciences, 7,* Article No. 20. https://doi.org/10.3390/geosciences7020020

Sasakova, N., Gregova, G., Takacova, D., Mojzisova, J., Papajova, I., Venglovsky, J. et al. (2018). Pollution of Surface and Ground Water by Sources Related to Agricultural Activities. *Frontiers in Sustainable Food Systems, 2,* Article No. 42. https://doi.org/10.3389/fsufs.2018.00042

Schnebelen, N., Platel, J. P., Le Nindre, Y., & Baudry, D. (2002). *Water Management in Aquitaine 5. Sectorial Operation. Oligocene Aquifer Protection in the Bordeau Region*. Rapport, BRGM.

Schult, J. (2016). *Herbicides, Pesticides and Nutrients in the Tindall Aquifer, Katherine Region*. Northern Territory Department of Land Resources Management, Report, (13).

Schürch, M., Bulgheroni, M., & Sinreich, M. (2018). Température des eaux souterraines: Un aperçu de l'état et de l'évolution en Suisse. *Aqua Gas, 7,* 40-48.

Sefie, A., Aris, A. Z., Shamsuddin, M. K. N., Tawnie, I., Suratman, S., Idris, A. N. et al. (2015). Hydrogeochemistry of Groundwater from Different Aquifer in Lower Kelantan Basin, Kelantan, Malaysia. *Procedia Environmental Sciences, 30,* 151-156. https://doi.org/10.1016/j.proenv.2015.10.027

Shalyari, N., Alinejad, A., Hashemi, A. H. G., RadFard, M., & Dehghani, M. (2019). Health Risk Assessment of Nitrate in Groundwater Resources of Iranshahr Using Monte Carlo Simulation and Geographic Information System (GIS). *MethodsX, 6,* 1812-1821. https://doi.org/10.1016/j.mex.2019.07.024

Shaw, M. S., Silburn, D. S., Lenahan, M., & Harris, M. (2012). *Pesticides in Groundwater in the Lower Burdekin Floodplain*. Department of Environment and Resource Management, Queensland Government.

Shi, L., & Jiao, J. J. (2014). Seawater Intrusion and Coastal Aquifer Management in China: A Review. *Environmental Earth Sciences, 72,* 2811-2819. https://doi.org/10.1007/s12665-014-3186-9

Shishaye, H. A. (2015). Simulations of Nitrate Leaching from Sugarcane Farm in Metahara, Ethiopia, Using the LEACHN Model. *Journal of Water Resource and Protection, 7,* 665-688. https://doi.org/10.4236/jwarp.2015.78055

Singh, A., Srivastav, S. K., Kumar, S., & Chakrapani, G. J. (2015). A Modified-DRASTIC Model (DRASTICA) for Assessment of Groundwater Vulnerability to Pollution in an Urbanized Environment in Lucknow, India. *Environmental Earth Sciences, 74,* 5475-5490. https://doi.org/10.1007/s12665-015-4558-5

Sivakarun, N., Udayaganesan, P., Chidambaram, S., Venkatramanan, S., Prasanna, M. V., Pradeep, K. et al. (2020). Factors Determining the Hydrogeochemical Processes Occurring in Shallow Groundwater of Coastal Alluvial Aquifer, India. *Geochemistry, 80,* Article ID: 125623. https://doi.org/10.1016/j.chemer.2020.125623

Sokegbe, O. Y., Djeri, B., Kogno, E., Kangnidossou, M., Mensah, R. T., Soncy, K. et al. (2018). Les risques sanitaires liés aux sources d'eau de boisson dans le district n°2 de Lomé-commune: Cas du quartier d'Adakpamé. *International Journal of Biological and Chemical Sciences, 11,* Article No. 2341. https://doi.org/10.4314/ijbcs.v11i5.31

Srinivasamoorthy, K., Gopinath, M., Chidambaram, S., Vasanthavigar, M., & Sarma, V. S. (2014). Hydrochemical Characterization and Quality Appraisal of Groundwater from Pungar Sub Basin, Tamilnadu, India. *Journal of King Saud University-Science, 26,* 37-52. https://doi.org/10.1016/j.jksus.2013.08.001

Stempvoort, D. V., Ewert, L., & Wassenaar, L. (1993). Aquifer Vulnerability Index: A GIS-Compatible Method for Groundwater Vulnerability Mapping. *Canadian Water Resources Journal, 18,* 25-37. https://doi.org/10.4296/cwrj1801025

Stigter, T. Y., Ribeiro, L., & Dill, A. M. M. C. (2006). Evaluation of an Intrinsic and a Specific Vulnerability Assessment Method in Comparison with Groundwater Salinisation and Nitrate Contamination Levels in Two Agricultural Regions in the South of Portugal. *Hydrogeology Journal, 14,* 79-99. https://doi.org/10.1007/s10040-004-0396-3

Su, H., Kang, W., Li, Y., & Li, Z. (2021). Fluoride and Nitrate Contamination of Groundwater in the Loess Plateau, China: Sources and Related Human Health Risks. *Environmental Pollution, 286,* Article ID: 117287. https://doi.org/10.1016/j.envpol.2021.117287

Sundaram, B., Feitz, A. J., de Caritat, P., Plazinska, A., Brodie, R. S., & Coram, J. (2009). *Groundwater Sampling and Analysis: A Field Guide*. Geoscience Australia.

Sunitha, V., Reddy, Y. S., Suvarna, B., & Reddy, B. M. (2022). Human Health Risk Assessment (HHRA) of Fluoride and Nitrate Using Pollution Index of Groundwater (PIG) in and around Hard Rock Terrain of Cuddapah, A.P. South India. *Environmental Chemistry and Ecotoxicology, 4,* 113-123. https://doi.org/10.1016/j.enceco.2021.12.002

Taghinia Hejabi, A., Basavarajappa, H. T., Karbassi, A. R., & Monavari, S. M. (2011). Heavy Metal Pollution in Water and Sediments in the Kabini River, Karnataka, India. *Environmental Monitoring and Assessment, 182,* 1-13. https://doi.org/10.1007/s10661-010-1854-0

Takal, J. K., & Quaye-Ballard, J. A. (2018). Bacteriological Contamination of Groundwater in Relation to Septic Tanks Location in Ashanti Region, Ghana. *Cogent Environmental Science, 4,* Article ID: 1556197. https://doi.org/10.1080/23311843.2018.1556197

Talib, M. A., Tang, Z., Shahab, A., Siddique, J., Faheem, M., & Fatima, M. (2019). Hydrogeochemical Characterization and Suitability Assessment of Groundwater: A Case Study in Central Sindh, Pakistan. *International Journal of Environmental Research and Public Health, 16,* Article No. 886. https://doi.org/10.3390/ijerph16050886

Tang, C., Chen, J., Shindo, S., Sakura, Y., Zhang, W., & Shen, Y. (2004). Assessment of Groundwater Contamination by Nitrates Associated with Wastewater Irrigation: A Case Study in Shijiazhuang Region, China. *Hydrological Processes, 18,* 2303-2312. https://doi.org/10.1002/hyp.5531

Taylor, C. A., & Stefan, H. G. (2009). Shallow Groundwater Temperature Response to Climate Change and Urbanization. *Journal of Hydrology, 375,* 601-612. https://doi.org/10.1016/j.jhydrol.2009.07.009

Teixeira, J., Chaminé, H. I., Espinha Marques, J., Carvalho, J. M., Pereira, A. J. S. C., Carvalho, M. R. et al. (2015). A Comprehensive Analysis of Groundwater Resources Using GIS and Multicriteria Tools (Caldas Da Cavaca, Central Portugal): Environmental Issues. *Environmental Earth Sciences, 73,* 2699-2715. https://doi.org/10.1007/s12665-014-3602-1

Telahigue, F., Souid, F., Agoubi, B., Chahlaoui, A., & Kharroubi, A. (2020). Hydrogeochemical and Isotopic Evidence of Groundwater Salinization in a Coastal Aquifer: A Case Study in Jerba Island, Southeastern Tunisia. *Physics and Chemistry of the Earth, Parts A/B/C, 118,* Article ID: 102886. https://doi.org/10.1016/j.pce.2020.102886

Teng, Y., Hu, B., Zheng, J., Wang, J., Zhai, Y., & Zhu, C. (2018). Water Quality Responses to the Interaction between Surface Water and Groundwater along the Songhua River, NE China. *Hydrogeology Journal, 26,* 1591-1607. https://doi.org/10.1007/s10040-018-1738-x

Thirumalaivasan, D., Karmegam, M., & Venugopal, K. (2003). AHP-DRASTIC: Software for Specific Aquifer Vulnerability Assessment Using DRASTIC Model and GIS. *Envi-*

ronmental Modelling & Software, 18, 645-656. https://doi.org/10.1016/s1364-8152(03)00051-3

Thirumalini, S., & Joseph, K. (2009). Correlation between Electrical Conductivity and Total Dissolved Solids in Natural Waters. *Malaysian Journal of Science, 28,* 55-61. https://doi.org/10.22452/mjs.vol28no1.7

Tiwari, A. K., Pisciotta, A., & De Maio, M. (2019). Evaluation of Groundwater Salinization and Pollution Level on Favignana Island, Italy. *Environmental Pollution, 249,* 969-981. https://doi.org/10.1016/j.envpol.2019.03.016

Todd, D. K. (2008). *Groundwater Hydrology* (3rd ed.). Wiley.

Tomer, T., Katyal, D., & Joshi, V. (2019). Sensitivity Analysis of Groundwater Vulnerability Using DRASTIC Method: A Case Study of National Capital Territory, Delhi, India. *Groundwater for Sustainable Development, 9,* Article ID: 100271. https://doi.org/10.1016/j.gsd.2019.100271

Vaux, H. (2011). Groundwater under Stress: The Importance of Management. *Environmental Earth Sciences, 62,* 19-23. https://doi.org/10.1007/s12665-010-0490-x

Vengosh, A., Gill, J., Lee Davisson, M., & Bryant Hudson, G. (2002). A Multi-Isotope (B, Sr, O, H, and C) and Age Dating (^{3}H-^{3}He and ^{14}C) Study of Groundwater from Salinas Valley, California: Hydrochemistry, Dynamics, and Contamination Processes. *Water Resources Research, 38,* 9-1-9-17. https://doi.org/10.1029/2001wr000517

Vespasiano, G., Muto, F., & Apollaro, C. (2021). Geochemical, Geological and Groundwater Quality Characterization of a Complex Geological Framework: The Case Study of the Coreca Area (Calabria, South Italy). *Geosciences, 11,* Article No. 121. https://doi.org/10.3390/geosciences11030121

Ward, M., Jones, R., Brender, J., De Kok, T., Weyer, P., Nolan, B. et al. (2018). Drinking Water Nitrate and Human Health: An Updated Review. *International Journal of Environmental Research and Public Health, 15,* Article No. 1557. https://doi.org/10.3390/ijerph15071557

Wolf-Gladrow, D. A., Zeebe, R. E., Klaas, C., Körtzinger, A., & Dickson, A. G. (2007). Total Alkalinity: The Explicit Conservative Expression and Its Application to Biogeochemical Processes. *Marine Chemistry, 106,* 287-300. https://doi.org/10.1016/j.marchem.2007.01.006

Wu, J., & Sun, Z. (2016). Evaluation of Shallow Groundwater Contamination and Associated Human Health Risk in an Alluvial Plain Impacted by Agricultural and Industrial Activities, Mid-West China. *Exposure and Health, 8,* 311-329. https://doi.org/10.1007/s12403-015-0170-x

Wu, J., Li, P., Qian, H., & Fang, Y. (2014). Assessment of Soil Salinization Based on a Low-Cost Method and Its Influencing Factors in a Semi-Arid Agricultural Area, Northwest China. *Environmental Earth Sciences, 71,* 3465-3475. https://doi.org/10.1007/s12665-013-2736-x

Wu, J., Lu, J., Wen, X., Zhang, Z., & Lin, Y. (2019). Severe Nitrate Pollution and Health Risks of Coastal Aquifer Simultaneously Influenced by Saltwater Intrusion and Intensive Anthropogenic Activities. *Archives of Environmental Contamination and Toxicology, 77,* 79-87. https://doi.org/10.1007/s00244-019-00636-7

Xiao, H., Tang, Y., Li, H., Zhang, L., Ngo-Duc, T., Chen, D. et al. (2021). Saltwater Intrusion into Groundwater Systems in the Mekong Delta and Links to Global Change. *Advances in Climate Change Research, 12,* 342-352. https://doi.org/10.1016/j.accre.2021.04.005

Xu, X., Xiong, G., Chen, G., Fu, T., Yu, H., Wu, J. et al. (2021). Characteristics of Coastal Aquifer Contamination by Seawater Intrusion and Anthropogenic Activities in the

Coastal Areas of the Bohai Sea, Eastern China. *Journal of Asian Earth Sciences, 217,* Article ID: 104830. https://doi.org/10.1016/j.jseaes.2021.104830

Xue, D., Botte, J., De Baets, B., Accoe, F., Nestler, A., Taylor, P. et al. (2009). Present Limitations and Future Prospects of Stable Isotope Methods for Nitrate Source Identification in Surface- and Groundwater. *Water Research, 43,* 1159-1170. https://doi.org/10.1016/j.watres.2008.12.048

Yang, Y., Toor, G. S., Wilson, P. C., & Williams, C. F. (2017). Micropollutants in Groundwater from Septic Systems: Transformations, Transport Mechanisms, and Human Health Risk Assessment. *Water Research, 123,* 258-267. https://doi.org/10.1016/j.watres.2017.06.054

Yanhui, L., Liang, T., Jing, W., & Xianqiua, L. (2012). Study on Water Resource Vulnerability Evaluation of Hani Terrace Core Area in Yuanyang, Yunnan. *Procedia Earth and Planetary Science, 5,* 268-274. https://doi.org/10.1016/j.proeps.2012.01.046

Yin, S., Xiao, Y., Han, P., Hao, Q., Gu, X., Men, B. et al. (2020). Investigation of Groundwater Contamination and Health Implications in a Typical Semiarid Basin of North China. *Water, 12,* Article No. 1137. https://doi.org/10.3390/w12041137

Zaisheng, H. (1998). Groundwater for Urban Water Supplies in Northern China—An Overview. *Hydrogeology Journal, 6,* 416-420. https://doi.org/10.1007/pl00010968

Zhang, Y., Li, F., Zhang, Q., Li, J., & Liu, Q. (2014). Tracing Nitrate Pollution Sources and Transformation in Surface- and Ground-Waters Using Environmental Isotopes. *Science of the Total Environment, 490,* 213-222. https://doi.org/10.1016/j.scitotenv.2014.05.004

Zhao, Y. Y., & Pei, Y. S. (2012). Risk Evaluation of Groundwater Pollution by Pesticides in China: A Short Review. *Procedia Environmental Sciences, 13,* 1739-1747. https://doi.org/10.1016/j.proenv.2012.01.167