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A review on the application of the DRASTIC method in the assessment of groundwater vulnerability

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ABSTRACT

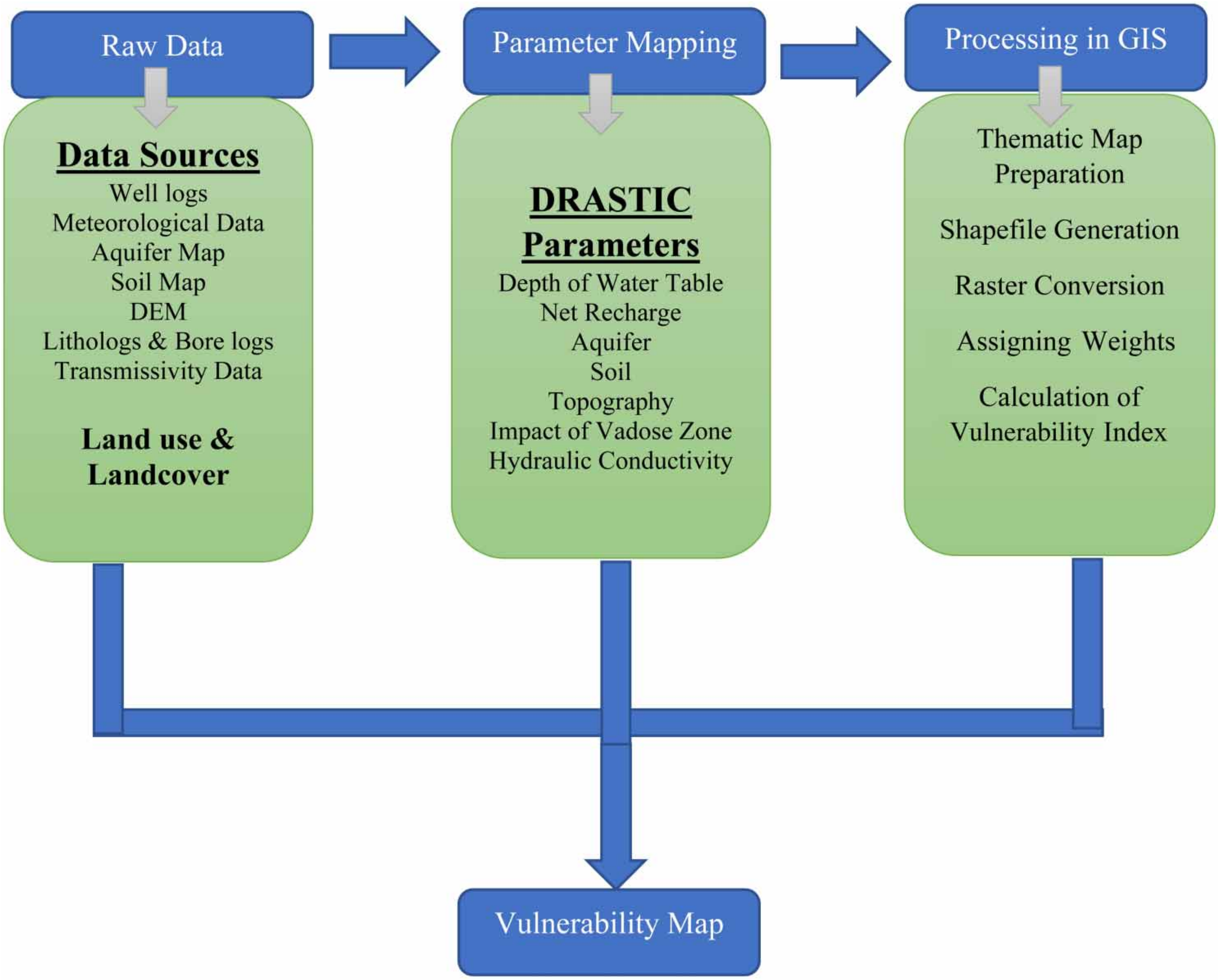
Industrial and municipal wastes, agricultural contamination owing to pesticides and chemical hazards, seawater intrusion in coastal areas, and other factors damage groundwater. In several towns and industrial clusters across India, this is becoming a rising subject of concern. Groundwater is difficult to contaminate, but once contaminated, it is difficult to clean up. It is critical to attain this goal using a variety of aquifer vulnerability assessment approaches. All of these strategies rely on process models as well as statistical or overlay index methodologies. Groundwater vulnerability is a major topic of discussion due to declining groundwater levels and rising contamination, posing a serious threat to the environment and water sources. To identify the risk and to assess the vulnerability, extensive research has been carried out among all the methods based on different parameters and different indexes. The DRASTIC method is one of the most important and accurate of the overlay and index methods for the assessment of groundwater vulnerability. This research study is a systematic analysis of the available research articles on the applications of the DRASTIC and Modified DRASTIC (DRASTIC-L) performance management process on Geographical Information Systems (GIS). This research also reveals research gaps in the various groundwater vulnerability assessment approaches, as well as their limits and hypotheses. This study discovered that integrating GIS with DRASTIC is the most effective and accurate way for determining groundwater vulnerability. In agricultural, arid, semi-arid, and basaltic zones, the modified DRASTIC model also outperforms the traditional DRASTIC model.

Key words: DRASTIC, GIS, groundwater, methods of overlay and index, vulnerability

HIGHLIGHTS

- Helpful in taking management decisions so as to afford early warning of quality degradation.
- Effective strategy for sustainable groundwater management.
- Increase the chances of reducing the gap between policy enhancement and enforcement.
- Improve the quality of groundwater and safe supply for use.
- Achieve sustainable water-use management.

GRAPHICAL ABSTRACT



INTRODUCTION

Water is very important to living organisms. So definitely water is called the life of human beings and all living creatures. Water is also called the origin of life. Groundwater is the most precious source of fresh water on the earth among all water sources. Nearly half of all drinking water on the globe comes from groundwater, and 43 percent of all water used for irrigation in agriculture comes from groundwater.

Among fresh water sources about 30.10% of water is available as groundwater. So, groundwater is a globally important and valuable renewable resource for human life and the economic development of humans as well as whole countries. In developing countries like India, groundwater contamination has become a serious concern in the post-industrialization era (Vijayakumar *et al.* 2022). Basically, groundwater is water that exists underground in saturated zones below the land surface. It is divided into two parts: the unsaturated zone and saturated zone. The unsaturated zone lies above the water table and the saturated zone lies below the saturated zone. The body of rock and/or sediment which holds the groundwater is called an aquifer.

THREATS TO GROUNDWATER

Groundwater systems are extremely dynamic, with water constantly moving downward due to the down-gradient from recharge to discharge sites. Nowadays for many different reasons groundwater is polluted and this creates a serious health hazard for the life of living creatures. Groundwater can be contaminated due to different types of human activities which include the disposal of sewage and leaching of pesticides and fertilizers, since due to increasing pesticides and fertilizers in agricultural fields, nitrate concentration may also increase. Pollution control and removal of pollutants from groundwater are a challenging and expensive task (Khodabakhshi *et al.* 2015), since after 1970 the exploitation of groundwater has also increased. According to the *World Water Development Report 2020* published by the United Nations Educational, Scientific, and Cultural Organization (UNESCO), India is the world's greatest extractor of groundwater. Groundwater levels in important aquifers have dropped dramatically, lowering stream flows and degrading riparian and wetland ecosystems. Other critical regions for global food security, such as the North China Plains, Rajasthan, Gujarat, Punjab, Haryana, and Andhra Pradesh in India, and Eastern Australia, are facing catastrophic groundwater losses. Groundwater has received insufficient attention when it comes to pollution protection, despite its importance as the most critical component of sustainable development. Groundwater vulnerability assessment is the best way to safeguard groundwater resources in places that are prone to pollution or are already contaminated (National Research Council 1993). Groundwater levels are depleting, requiring long-term development planning to protect these crucial resources (Narendra & Rao 2006).

Groundwater is mostly affected by human activities. The velocity of groundwater below earth strata is much less and so the flow of contamination also reduces in the groundwater. Contamination flow is measured by the advection cohesion equation, which gives an idea about the velocities and flow of the contaminant with the groundwater. When the aquifer system is the fracture type of aquifer system then the velocities of the groundwater flow become higher and vice versa. Velocities of the groundwater flow also depend on the aquifer type, soil strata, topography, recharge rate etc. Velocities can be measured in kilometres per day in limestone with a well-developed solution or in some volcanic aquifers with extensive lava tubes or cooling fissures. Soil stratum is a critical component for contaminants that degrade over time, both for providing groundwater velocity and for controlling disease-causing microbes such as bacteria, viruses, and protozoa (Morris *et al.* 2003).

The primary risks to groundwater sustainability are the continual rise in water demand owing to population growth and increased agricultural productivity. To meet the water requirement, roughly 40% of India's land area is irrigated utilizing massive canal water delivery networks. Between 1950 and 2001, India's irrigated land increased from 23 Mha to 80 Mha (Chowdary *et al.* 2005), due to increase in the population food demand also increasing and due to the usage of fertilizers and pesticides also increasing day by day. From 1950 to 2001 the usage of chemical fertilizers and pesticides in India increased from 50 million tons to 210 million tons. So, seepage and deep percolation also reduce the quality of the groundwater.

India is a developing country. So, the urbanization and the industrialization of the country also affect groundwater quality. In many Indian towns and industrial clusters, groundwater pollution caused by industrial effluent and municipal waste in water bodies is a major concern. According to the Central Pollution Control Board's 1995 survey, groundwater at 22 sites across 16 Indian states has been contaminated by industrial effluent.

As shown in Figure 1, solid waste disposal on land surfaces could be another source of groundwater pollution. The toxic minerals of the solid waste can seep into the groundwater via soil and affect the groundwater quality. Also, in landfill the metal content also degrades the quality.

NEED FOR GROUNDWATER VULNERABILITY ASSESSMENT

Despite threats from potentially harmful activities, groundwater is often surprisingly resilient, and water quality is generally high throughout broad areas of the globe. Sometimes groundwater naturally minimizes the impacts of contamination in specific aquifer types. Groundwater is difficult to contaminate, but once it is, it is tough to rehabilitate. The intrinsic qualities that govern the sensitivity of the water to be adversely affected by the applied contaminated load are referred to as groundwater vulnerability.

In addition, the cost of a failing local aquifer is very significant, and its loss may put a strain on other water supplies that are being considered as replacements. As a result, in the poor world, it is both costly and impractical. As a result, assessing which aquifer systems and ecosystems are the most vulnerable to degradation is crucial. Vulnerability assessment has proven to be an efficient and cost-effective tool for protecting groundwater resources from contamination (Machiwal *et al.* 2018). Studies of vulnerability provide insight into the effects of pollution loading, whether severe or light. Lobo-Ferreira & Cabral (1991) termed groundwater pollution vulnerability to be defined in accordance with the conclusions and recommendations of the International Conference on the Vulnerability of Soil and Groundwater Pollutants.

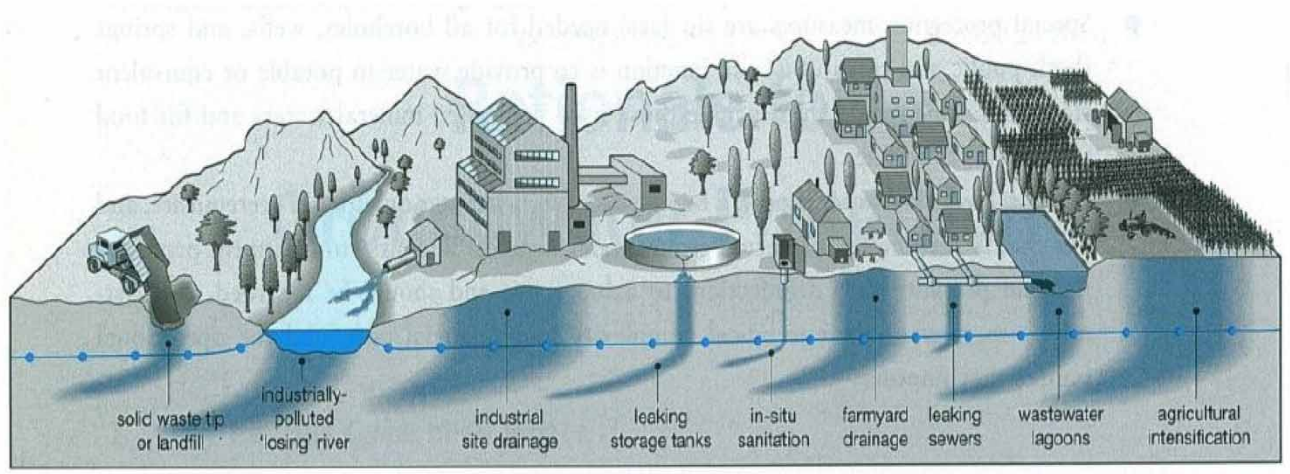


Figure 1 | Groundwater pollution factors. (*Source*: Foster 1998).

GROUNDWATER VULNERABILITY ASSESSMENT METHODS

The notion is of assessing groundwater vulnerability in places that are more susceptible to pollution than others (Piscopo 2001). There are various sorts of vulnerability assessment methodologies that are utilized depending on the situation of the place. In many regions of the world, process-based methods, statistical methods, and overlay and index methods are commonly employed to assess groundwater risk.

Overlay and index methods

Due to the low requirement of field data, the overlay and index approaches are the most important and accurate methods for determining vulnerability mapping. This strategy takes into account all of the variables that influence the groundwater vulnerability in a specific area. Different physical and hydrological parameters are used in this strategy to restrict the passage of contaminants that impair groundwater quality through the unsaturated zone until the water table is reached (Aller *et al.* 1987). The process of vulnerability mapping is very easy and less time-consuming as well as requiring less data, so these methods are most preferable. These methods are easy but in spite of this there are certain limitations of the overlay and index methods. Among them the first limitation is that these methods assume linear relationships between the vulnerability and the parameters while they show a non-linear superposition relation (Neukum & Azzam 2009). Secondly, all the weights of the parameters require the proper subjective judgement, which requires experience, and this directly affects the result of the vulnerability (Frind *et al.* 2006). Finally, the ratings' values are discredited, introducing an inaccuracy in the vulnerability mapping. There are many overlay and index methods, and among them DRASTIC (Aller *et al.* 1987), SINTACS (Civita & De Maio 1997), GOD (Foster 1998), AVI (Stempvoort *et al.* 1993), and PI (Goldscheider *et al.* 2000) are the commonly used and known methods.

Process-based simulation methods

In these methods of vulnerability mapping, predictions of the contaminant flow are done by a different technique. Basically, the data of the process-based methods are found out by different indirect techniques (Barbash & Resek 1996). These methods work based on the advection–dispersion methods for contaminant transport in groundwater. Process-based simulation models require analytical or numerical solutions to mathematical equations that demonstrate linked processes affecting contaminant transport. Basically, there are different approaches of the simulation methods, including saturated–unsaturated, single phase–multiple phases as well as one-dimensional–two-dimensional–three-dimensional models. Based on a one-dimensional advection–dispersion transport model that replicates vertical movement through a soil to the water table, Meeks & Dean (1990) created a leaching potential index. Soutter & Pannatier (1996) defined groundwater susceptibility as the ratio of cumulative pesticide flow reaching mean water table depth to total pesticide applied. Visual ModFlow is a physical-based model that forecasts water flow and pollution transfer under various hydrologic circumstances. This method produces superior results, but it has the drawback of requiring a large amount of input data, as well as more complicated computational processes and calibration issues (Iqbal *et al.* 2012).

Statistical methods

Due to the complexities of groundwater vulnerability, there are different types of factors and parameters and so the statistical methods are suitable only in specific regions. They establish a link between explanatory variables and pollution concentrations (McLay *et al.* 2001). Basically, statistical methods use different parameters which work on the basis of probability and their results are also expressed as probability. Different probabilistic models are used in these types of methods. Multiple independent variables are used in these models, with the dependent variable being a pollutant concentration or a likelihood of contamination (Iqbal *et al.* 2012). A logistic regression model including soil-texture-related independent variables was proposed by Teso *et al.* (1996). The vulnerability assessment is done using dependent and independent variables in this method. In this method, the dependent variable is the variable, which is defined as the contamination status of soil sections (uncontaminated vs contaminated), and groundwater vulnerability is assessed by predicting the probability of a section containing a contaminated well (Teso *et al.* 1996). Worrall & Kolpin (2004) developed a groundwater contamination logistic regression model that combines chemical property fluctuation with land use, soil, and aquifer parameters. Compared with the overlay and index methods, the statistical method and the simulation models give better results and the only concern is about the input data or the availability of the data (Focazio *et al.* 2008).

As shown in Table 1, names of the procedures are usually made up of letters that represent the layer being processed; a list of acronyms is given as used in these approaches.

Table 1 | Methods for groundwater vulnerability assessment

DRASTIC	**D**epth to water table net **R**echarge **A**quifer media **S**oil media **T**opography **I**mpact of vadose zone hydraulic **C**onductivity
GOD	**G**roundwater occurrence **O**verlying lithology **D**epth to water table
SINTACS	**S** – water table depth **I** – effective infiltration **N** – unsaturated conditions **T** – soil media **A** – aquifer hydrogeologic characteristics **C** – hydraulic conductivity **S** – topographic slope
EPIK	**E**pikarst **P**rotective cover **I**nfiltration conditions **K**arst network
PI	**P**rotective cover **I**nfiltration condition
ISIS	**I**nfiltration **S**oil type L**i**thology **S**oil thickness
AVI	**A**quifer **V**ulnerability **I**ndex

DRASTIC MODEL FOR VULNERABILITY ASSESSMENT

DRASTIC is a parametric vulnerability mapping technique that is well known and widely used. It was created in the United States as part of an EPA (Environmental Protection Agency) effort with the goal of assisting managers, planners, and administrators. Because of the minimal cost of deployment and the ease with which data may be collected, DRASTIC can be employed in a wide range of locations (Aller *et al.* 1987). Panagopoulos *et al.* (2006) claim that 'the selection of many parameters and their interrelationship decreases the probability of ignoring some important parameters, restricts the effect of an incidental error in the calculation of a parameter and so enhances the statistical accuracy of the model'. This method is a well-known overlay and index method that evaluates intrinsic vulnerability based on the physical and hydrogeological properties of the aquifer (Aller *et al.* 1987). The DRASTIC approach is simple to use, and numerous researchers have used it to assess groundwater vulnerability all across the world. The DRASTIC model is used in many parts of the worlds such as Africa, Indonesia, India, Iran, Iraq, Jordan, Europe, and the USA. Basically, in this model seven parameters are used for the assessment of vulnerability. These model parameters are considered for the ratings and weights of the parameters and give the DRASTIC index value (Rosen 1994). D stands for depth of water, R for net recharge, A for aquifer, S for soil, T for topography, I for vadose zone impact, and C for conductivity in DRASTIC. Figure 2 denotes the different parameters which are used in the DRASTIC modelling.

The DRASTIC model is a valuable tool for assessing groundwater vulnerability and, more typically, for research purposes. Over time there has been work on the basis of modification and the including of different parameters which gave better results and accuracy in the assessment of vulnerability. Also, at the time of first introduction of the DRASTIC method and model, Aller *et al.* (1987) used different hypotheses or we can say assumptions, and some hypotheses among them are listed below.

- At the earth's surface, the pollutant is released (use of fertilizers, burning of coal and leaching of metals from coal-ash tailings etc.).
- The pollutant is transferred into the groundwater by rainfall.
- The pollutant moves simultaneously with water.
- The affected area should be at least 100 acres (0.4 square kilometres).

Based on the hypothesis of the DRASTIC model some limitations are also included in this modelling of the vulnerability assessment, some of which among them are included here.

- The vulnerability index is calculated using the DRASTIC model, which includes seven criteria, each with its own weight and rating value. Because the model does not account for the influence of specific area factors, some of the weights and rates are considered universally, and we may conclude that it is not accurate for a detailed examination of groundwater vulnerability assessment.
- There is no standard algorithm for testing and validating the model in the environment for aquifers.
- It is expressively designed for use in GIS software. The first time the DRASTIC model was used with GIS was by Merchant *et al.* (1987).
- Each parameter is weighted based on the standard value and the standard weights, so it is not so accurate for all areas related to the groundwater contamination.
- It is not so applicable for a study area of less than 100 acres.

The following Equation (1) calculates the DRASTIC index using a linear combination of all parameters.

$$DI = D_{\mathrm{w}}\, D_{\mathrm{R}} + R_{\mathrm{w}}.\, R_{\mathrm{R}} + A_{\mathrm{w}}.\, A_{\mathrm{R}} + S_{\mathrm{w}}.\, S_{\mathrm{R}} + T_{\mathrm{w}}.\, T_{\mathrm{R}} + I_{\mathrm{w}}.\, I_{\mathrm{R}} + C_{\mathrm{w}}.\, C_{\mathrm{R}} \tag{1}$$

where DI = DRASTIC index

D = depth of water table
R = net recharge
A = aquifer
S = soil
T = topography
I = impact of vadose zone

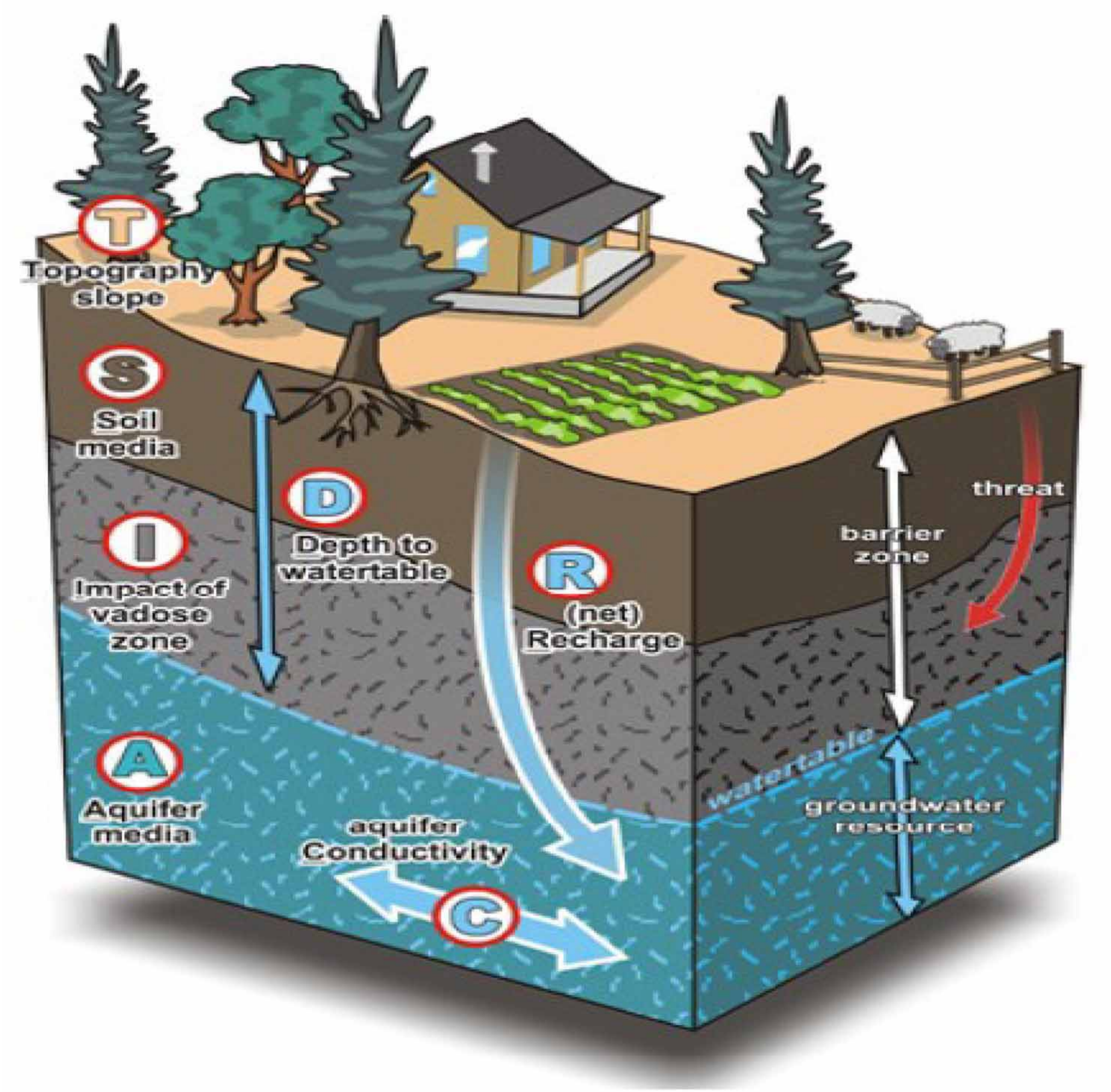


Figure 2 | DRASTIC parameters definition. (*Source*: www.frakturmedia.net).

C = conductivity
Subscript w = weight of the parameters
Subscript R = rate of the parameters

The DRASTIC index is a dimensionless metric that assesses the vulnerability of groundwater to pollution. If the value of the DRASTIC index higher then we can say that the area is more affected by pollution and if the value of the DRASTIC index is lower then the area is less affected by pollution. Basically, the range of the DRASTIC index is between 70 and 200.

Here the methods of measurements of the DRASTIC parameters and how they affect the groundwater vulnerability assessment are explained below.

DEPTH OF WATER TABLE (D)

Depth of water table is an important parameter of the DRASTIC model which is defined as the distance from the ground surface to the water table (Aller *et al.* 1987). In the aquifer, it is the vertical distance from the ground surface to the water table, or top of the saturated zone. It is calculated using the country's topography and contour map as well as the study area's topography and contour map. In India the Central Ground Water Board (CGWB) and state ground water bodies give data of the depth of water table. The general concept is that if the depth of the water table is greater then the chances of pollution are much less and vice versa because if the depth of water table is decreased then the pollutants easily reach the groundwater and pollute it.

NET RECHARGE (R)

The quantity of rainwater that infiltrates into the ground and reaches the groundwater table is referred to as net recharge. It serves as a channel for solid and liquid pollutants to flow through. The groundwater recharge for the study is estimated using two methods: one provided by the Ground Water Resources Estimation Committee, which was established under the National Water Policy by the Ministry of Water Resources, Government of India, and the other provided by various researchers, in which the recharge is determined using runoff, evapotranspiration, and precipitation values.

Method 1: given by Ministry of Water Resources

Basically this method gives the broad concept of the net recharge. In this method net recharge is find from another four to five parameters, which are the following:

a. Recharge due to rainfall
b. Recharge due to canal seepage
c. Recharge due to return flow from land under irrigation
d. Recharge due to river
e. Recharge due to tanks and ponds.

Recharge from rainfall

According to Equation (2), the typical infiltration method was used to determine the recharge from rainfall:

$$Rrf\ (\text{mcm}) = \text{normal rainfall in monsoon season (mm)} \times A \times f \tag{2}$$

where Rrf = recharge due to rainfall (in mcm)

A = area for which the recharge was calculated (in sq km)
f = factor of rainfall infiltration.

Recharge due to canal seepage

The recharging from canal seepage usually starts at the branch canal and continues through the branch minor, distributary, sub-distributary, and minor canals. This can be determined using *Rcs* Equation (3) below:

$$Rcs\ (\text{mcm/year}) = WA \times \text{days of canal run} \times \text{seepage factor} \tag{3}$$

where Rcs = recharge due to canal seepage (in mcm/year)

WA = the canal section's wetted area (in million sq m)
Days of canal run = no. of days of canal carrying discharge (in days)
Seepage factor = 0.3 (cubic m/million sq m) as recommended by the Ministry of the Water Resources.

Recharge due to return flow from land under irrigation

Water from irrigated fields seeps into the ground, causing fertilizers and pesticides to drain into the soil and eventually into the water table. The command areas under the branch canal, branch minor, distributary, sub-distributary, and minor are taken into account when calculating the recharge from irrigated land. From a general approach, the recharge from return flow is computed as 35 percent of the water given at the outlet for use in the field.

Recharge due to river

Recharge is also done by the river so it is an important parameter in finding out the net recharge value. Basically, recharge from the river is found from government reports on the river and river infiltration data or reports from bridge construction on the river. In general, according to the Ministry of the Water Resources, the recharge from the river is taken as 10 to 15 m/year for the major river and for the tributaries or the minor river it is taken as 5 to 10 m/year.

Recharge from tanks and ponds

The recharge from tanks, ponds, and other water bodies was also digitized using an IRS-P6 satellite picture with a LISS-III sensor with a spatial resolution of 23.5 m or 30 m. The following Equation (4) is used to determine the recharge from tanks and ponds:

$$Rwb = 44 - 60\ \text{cm/year} \times \text{average area of the water spread of tanks and ponds} \tag{4}$$

where Rwb = recharge from the water bodies.

$$\begin{aligned}\text{The total recharge (R) (in mcm)} &= \text{recharge due to rainfall} + \text{recharge due to canal seepage}\\ &+ \text{recharge due to return flow from land under irrigation}\\ &+ \text{recharge due to river} + \text{recharge due to the tanks and ponds}\end{aligned} \tag{5}$$

Using Equation (5) net recharge data are effectively found.

This method of finding the net recharge data has been applied by researchers like Arora *et al.* (1996), Shirazi *et al.* (2013), and Khakhar *et al.* (2017) in their respective study areas.

Method 2: from water balance equation or from runoff values

In this method, net recharge is calculated from meteorological data for various time periods using the following Equation (6), which was developed by Mehta *et al.* (2006) in their research area:

$$NR = P - ET - R_o \tag{6}$$

where NR = net recharge

P = annual precipitation (in mm/year)
ET = evapotranspiration (in mm/year)
R_o = total runoff (in mm).

In this method, precipitation and evapotranspiration data is collected from the different websites like WRIS, NASA Earth data etc. Total runoff is also calculated according to the different methods which are given by different researchers and different authors. Among all methods of runoff calculation, the SCS-CN method is the most suitable method, as has been applied by Ali (2007).

Net recharge is the main factor in contaminants reaching the aquifer. Greater recharge indicates the possibility of contaminants reaching the groundwater and affecting the groundwater quality (Aller *et al.* 1987). River leakage or rainfall are the two main sources of recharging.

AQUIFER (A)

This is another crucial parameter for determining groundwater vulnerability. The material property or kind of aquifer present in the study area is referred to as aquifer media. The geological map of the basin and lithologs of the study area or bore logs in the study area are used to create the aquifer media. Aquifer is defined by Aller *et al.* (1987) as a geological formation that produces enough water for human consumption. Consolidated and unconsolidated rocks (such as sand, gravel, or limestone) that act as an aquifer are referred to as aquifer media. Controlling the route, path length, and movement of pollutants requires this parameter. Pollution sensitivity can be raised by a variety of factors, including sediment size, permeability, and attenuation capacity. Geological data can be used to create an aquifer media map.

SOIL (S)

Soil media is defined as the soil which is present in the uppermost part of the ground. The top, weathered portion of the unsaturated zone with substantial biological activity is represented by the soil media (Aller *et al.* 1987). It is the vadose zone's top layer, and its features are important in determining potential contamination, whereas increasing soil depth decreases infiltration. In general, a soil map can reflect pollutant infiltration rates. The type of clay, the grain size, and the shrink potential of clay are all important elements in determining the potential contamination of soil. Indeed, aquifer vulnerability is reduced when there is less clay, less shrinkage potential, and smaller particle size.

TOPOGRAPHY (T)

The slope of the terrain in the research area is known as topography. Topography directly or indirectly affects the runoff of contaminants. If the slope of the area is steep then the recharge of the water is decreased and contaminants are also reduced, so it is an important factor in assessing the groundwater vulnerability (Aller *et al.* 1987). GIS tools can determine slope and use a digital elevation model (DEM) to create topography maps.

IMPACT OF VADOSE ZONE (I)

The unsaturated zone, also known as the vadose zone, is described as the area between the aquifer and the soil cover. Vertical movement of the water in the unsaturated zone of the soil is the main cause of contaminant transport in groundwater and so this factor is very important for the groundwater vulnerability assessment. The unsaturated zone's characteristics can influence the media's attenuation qualities above the water table. The subsurface geology and lithological properties of drilling logs are also used to create a vadose zone map.

HYDRAULIC CONDUCTIVITY (C)

The ability of an aquifer to carry water is known as hydraulic conductivity. A hydraulic conductivity distribution map is created using the results of the pumping test and lithology (Aller *et al.* 1987). Contaminant migration is controlled by permeability. In India, hydraulic conductivity is found then drafted in the Central Ground Water Board reports as well as state groundwater reports by different government organizations like the Central Ground Water Board as well as state groundwater boards. Greater pollutant transport and distribution can be seen in areas with higher hydraulic conductivity. Pore gaps and fractures inside the aquifer also play a role.

Hydraulic conductivity is also found from the following Equation (7):

$$C = T/b \tag{7}$$

where $C =$ hydraulic conductivity (m/day)

$T =$ transmissivity (sq m/day)
$b =$ aquifer thickness (m).

In order to construct the aquifer vulnerability index, the DRASTIC technique assigns a precise weight and rate to each parameter. The groundwater vulnerability map is prepared and vulnerable areas are classified according to Table 2 (Aller *et al.* 1987) and Table 3 (Engel *et al.* 1996), and then the vulnerability classes are defined as indicated in Table 4, after assigning the

Table 2 | Vulnerability assessment criteria using the DRASTIC approach

Class Vulnerability	Low	Moderate	High	Very High
Calculated index value	47–92	93–136	137–184	>184

Source: Aller *et al.* (1987).

Table 3 | Vulnerability assessment criteria based on the DRASTIC method

Class Vulnerability	Low	Average	High	Very High
Calculated index value	<101	101–140	141–200	>200

Source: Engel *et al.* (1996).

Table 4 | Definition of a vulnerability class

Vulnerability class	Corresponding definition
Extreme	Most water pollutants are vulnerable to it, and it has a rapid impact in many contamination scenarios.
High	In various pollution settings, it is vulnerable to a wide range of contaminants (excluding those that are easily absorbed or converted).
Moderate	Some contaminants make it vulnerable, but only if they are discharged or leached on a regular basis.
Low	Only when conservative pollutants are continually and widely emitted or leached are they vulnerable to conservative pollutants in the long run.
Negligible	There are no substantial vertical groundwater flow leakages in the confining beds.

weights as shown in Table 5 (Aller *et al.* 1987). Ranges of the different parameters are indicated in Table 6 (Aller *et al.* 1987). Aller *et al.* (1987) suggest different colour-coding for the vulnerability map preparation and this is included in Table 7.

MODIFICATIONS IN THE DRASTIC METHOD

Vulnerability mapping using the DRASTIC technique has a number of shortcomings, despite its ease of use and popularity. The biggest disadvantage is its subjective nature, which raises questions about the selection of specific factors and the exclusion of others (Panagopoulos *et al.* 2006). DRASTIC has been criticized for the following reasons:

- By giving equal rates and weights to parameters, it ignores the effect of regional characteristics.
- A standard validation approach is not used in this procedure.
- The parameters were chosen based on qualitative assessment rather than quantitative research.

As a result, a number of researchers have worked to improve the DRASTIC model so that a more accurate vulnerability assessment may be obtained. Some investigations, for example, compared the DRASTIC index with chemical or pollutant data, but found no link in most situations. McLay *et al.* (2001) stated that models like DRASTIC, which include a land management index, could be effective for predicting locations where groundwater monitoring should be more intensive. It has also been suggested that further research into the association between nitrate leaching measures from various land use activities and groundwater nitrate concentrations below these activities is required (McLay *et al.* 2001). In a GIS setting,

Table 5 | DRASTIC model parameters and their weights

Parameter	Weights
Depth of water	5
Net recharge	4
Aquifer media	3
Soil media	2
Topography	1
Impact of vadose zone	5
Hydraulic conductivity	3

Source: Aller *et al.* (1987).

Table 6 | Standard DRASTIC parameters

Layer	Range	Rating	Typical rating	Weight
Depth to water (m)	0–1.5	10		5
	1.5–4.5	9		
	4.5–9	7		
	9–15	5		
	15–22.5	3		
	22.5–30	2		
	>30	1		
Recharge (mm/y)	>254	9		4
	178–254	8		
	102–178	6		
	51–102	3		
	0–51	1		
Aquifer media	Karst limestone	9–10	10	3
	Basalt	2–10	9	
	Sand and gravel	4–9	8	
	Massive limestone	4–9	6	
	Massive sandstone	4–9	6	
	Bedded sandstone, limestone and shale sequences	5–9	6	
	Glacial till	4–6	5	
	Weathered metamorphic/igneous	3–5	4	
	Metamorphic/igneous	2–5	3	
	Massive shale	1–3	2	
Soil media	Thin or absent	10		2
	Gravel	10		
	Sand	9		
	Peat	8		
	Shrinking and/or aggregated clay	7		
	Sandy loam	6		
	Loam	5		
	Silty loam	4		
	Clay loam	3		
	Muck	2		
	Non-shrinking and non-aggregated clay	1		
Topography (%)	0–2	10		1
	2–6	9		
	6–12	5		
	12–18	3		
	>18	1		
Impact of vadose zone	Karst limestone	8–10	10	5
	Basalt	2–10	9	
	Sand and gravel	6–9	8	
	Metamorphic/igneous	2–8	4	
	Sand and gravel with significant silt	4–8	6	
	Bedded sandstone, limestone and shale	4–8	6	
	Sandstone	4–8	6	
	Limestone	2–7	6	
	Shale	2–5	3	
	Silt/clay	2–6	3	
	Confining layer	1	1	
Hydraulic conductivity (m/day)	>82	10		3
	41–82	8		
	29–41	6		
	12–29	4		
	4–12	2		

Source: Aller *et al.* (1987).

Table 7 | Colour codes for DRASTIC indices

Indices	Colour
<79	Violet
79–99	Indigo
100–119	Blue
120–139	Dark green
140–159	Light green
160–179	Yellow
180–199	Orange
>200	Red

Source: Aller *et al.* (1987).

Panagopoulos *et al.* (2006) revised the factor weightings and ratings of all DRASTIC parameters using simple statistical and geostatistical methodologies. There are lots of different parameters which affect groundwater quality; hydraulic conductivity is one of them but it less affects the quality. In some research work, hydraulic conductivity was removed from the DRASTIC equation for its improvement, and land use was added as a new DRASTIC component. When compared with the conventional technique, the correlation coefficient between the groundwater vulnerability index and nitrate concentrations was dramatically boosted, rising by 33% (Panagopoulos *et al.* 2006). The standard method with the addition of land-use was improved to assess the specific vulnerability using the DRASTIC-LU model (Wei *et al.* 2021). The DRASTIC scores for groundwater nitrate concentration were published by Leone *et al.* (2009). The scores were divided into two groups: lower vulnerability (60–80) with no nitrate content and higher vulnerability (110–155) with a wide range of nitrate concentrations ranging from around 0 to over 160 mg/L. The obligation to undertake interpolation of restricted field data, which involves interpolation error, is one of the main sources of this imbalance. As a result, DRASTIC results should be modified to fit location and pollutant specifications. For this purpose, several methods for developing and modifying the DRASTIC algorithm have been suggested.

SENSITIVITY ANALYSIS

DRASTIC is a vulnerability assessment method that uses seven hydrogeological layers, which some researchers claim can reduce error and uncertainty in the final vulnerability assessment (Rosen 1994). Other researchers claim that integrating a smaller number of characteristics would result in a more accurate vulnerability assessment (Barber *et al.* 1993). In the meantime sensitivity analysis can be used to determine the parameters needed for DRASTIC vulnerability mapping. The map removal sensitivity analysis, introduced by Lodwick *et al.* (1990), and the single parameter sensitivity analysis (SPSA), introduced by Napolitano & Fabbri (1996), are two types of sensitivity analysis. The map removal sensitivity analysis, which is done using Equation (8), evaluates the vulnerability map's sensitivity to removing one or more layers:

$$S = \left(\frac{\left| \frac{v}{N} - \frac{v'}{N} \right|}{v} \right) \times 100 \tag{8}$$

S stands for sensitivity index, *V* for unperturbed vulnerability index, *V*' for perturbed vulnerability index, and *N* and *n* for the number of data layers used to compute *V* and *V*'. Unperturbed vulnerability refers to the genuine vulnerability index calculated using all seven criteria, whereas perturbed vulnerability refers to the vulnerability estimated using fewer data layers (Babiker *et al.* 2005).

Each layer in the vulnerability index is assessed by the SPSA. It is also feasible to compare each parameter's theoretical and effective weight. Equation (9) is used to calculate the effective weight of each parameter:

$$w = \left(\frac{P_{\mathrm{r}} P_{\mathrm{w}}}{v} \right) \times 100 \tag{9}$$

where W denotes the effective weight of each parameter, P_r and P_w denote the rating value and weight of each parameter, respectively, and V is the total vulnerability index (Babiker *et al.* 2005).

In recent years, sensitivity analysis has been used in a number of studies to change the weight values specified in the DRASTIC approach to increase assessment accuracy and dependability (Abdullah *et al.* 2016; Barzegar *et al.* 2016). For non-point-source pollution, Neshat *et al.* (2014a, 2014b) used SPSA to modify the weights of the DRASTIC model, concluding that the modified DRASTIC model performed better than the standard method. For the Kerman Plain in Iran, the correlation between the vulnerability index and nitrate concentration was 82 percent after correction, compared with 44 percent before modification, according to the regression coefficients. Pacheco *et al.* (2015) used the modified DRASTIC technique to evaluate sensitivity analysis on 26 aquifer systems in Portugal. As a result, vulnerability indices were on average 20% lower than the initial DRASTIC values (Pacheco *et al.* 2015). The removal of the impact of the vadose zone, the depth to water, the hydraulic conductivity, and the net recharge created a considerable difference in the mapping vulnerability, according to Ouedraogo *et al.* (2016), who utilized sensitivity analysis in aquifer systems in Africa. They also revealed that the data on nitrate concentrations are favourably associated with the intrinsic vulnerability index, with a correlation coefficient of 0.94. Furthermore, Abdullah *et al.* (2016) used sensitivity analysis in the Halabja Said Sadiq Basin in Iraq's northeast and found that the modified DRASTIC was far superior to the standard model. The modified DRASTIC index and nitrate concentration have a good relationship, with Pearson correlation factors of 0.69, 0.57, and 0.72 for modified rate (using nitrate concentration), weight (sensitivity analysis), and combined rate–weight techniques, respectively.

CONCLUSION

The overlay index models are less constrained by data shortages and computational challenges than the other approaches of groundwater vulnerability assessment statistical-inference-based models, but they have a number of conceptual shortcomings. Sometimes there are many different parameters that are used for the calculation of the indices, which gives an idea of vulnerability, but the availability of the data is very difficult and if some data are not available than they are assumed according to the field conditions and this creates errors in the actual results. Also, weighting and validation are very difficult for the parameters.

So according to the whole research on groundwater vulnerability assessment and within it especially research on the DRASTIC model, we can say that the DRASTIC model is a very accurate and easy as well as reliable method for groundwater vulnerability assessment. Modifications are essential in both the approach and the model. The finest results come from modification according to field investigations. In arid, semi-arid, basaltic, agricultural, and landfill zones, the modified DRASTIC approach outperforms the traditional DRASTIC method. The DRASTIC approach benefits greatly from sensitivity analysis. It identifies which parameter has the most impact on groundwater vulnerability. Sensitivity analysis demonstrates the discrepancies between theoretical and effective weights of DRASTIC parameters. Also the parameter calculation method is the main important part of the research and so based on the field conditions it is very important to select appropriate methods for calculation of the parameters. Also the model is validated using the basic parameters of the drinking water, and in agricultural areas nitrate concentration and carbonate concentration are also used for validation purposes.

This may improve the prospects of reducing the gap between policy enactment and implementation, which is frequently a barrier to attaining long-term water usage sustainability.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

Abdullah, T. O., Ali, S. S. & Al-Ansari, N. A. 2016 Groundwater assessment of Halabja Saidsadiq Basin, Kurdistan region, NE of Iraq using vulnerability mapping. *Arabian Journal of Geosciences* **9** (3), 223.

Ali, S. S. 2007 Geology and Hydrogeology of Sharazoor-Piramagroon Basin in Sulaimani Area, Northeastern Iraq. PhD thesis (unpublished), Faculty of Mining and Geology, University of Belgrade, Belgrade, Serbia.

Aller, L., Lehr, J. H., Petty, R. & Bennett, T. 1987 *DRASTIC: A Standardized System to Evaluate Ground Water Pollution Potential Using Hydrogeologic Settings*. In: *Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection and Restoration*, National Water Well Association, Worthington, OH, USA, pp. 38–57.

Arora, P. K., Rawat, S. N., Chhabra, S. S. & Prakash, S. 1996 Evaluation of recharge to groundwater due to applied irrigation under different crops in Uttar Pradesh using isotope tracer technique – a field study. In: *Subsurface-Water Hydrology* (V. P. Singh & B. Kumar, eds), Springer, Dordrecht, The Netherlands, pp. 119–130.

Babiker, I. S., Mohamed, M. A. A., Hiyama, T. & Kato, K. 2005 A GIS-based DRASTIC model for assessing aquifer vulnerability in Kakamigahara Heights, Gifu Prefecture, central Japan. *Science of the Total Environment* **345** (1–3), 127–140.

Barbash, J. E. & Resek, E. A. 1996 *Pesticides in Ground Water: Distribution, Trends, and Governing Factors*. Ann Arbor Press, Chelsea, MI, USA.

Barber, C., Bates, L. E., Barron, R. & Allison, H. 1993 Assessment of the relative vulnerability of groundwater to pollution: a review and background paper for the conference workshop on vulnerability assessment. *AGSO Journal of Australian Geology & Geophysics* **14** (2–3), 147–154.

Barzegar, R., Moghaddam, A. A. & Baghban, H. 2016 A supervised committee machine artificial intelligent for improving DRASTIC method to assess groundwater contamination risk: a case study from Tabriz plain aquifer, Iran. *Stochastic Environmental Research and Risk Assessment* **30** (3), 883–899.

Chowdary, V. M., Rao, N. H. & Sarma, P. B. S. 2005 Decision support framework for assessment of non-point-source pollution of groundwater in large irrigation projects. *Agricultural Water Management* **75** (3), 194–225.

Civita, M. & De Maio, M. 1997 *SINTACS. Un sistema parametrico per la valutazione e la cartografia della vulnerabilitá degli acquiferi all'inquinamento. Metodologia e automatizzazione*. Pitagora, Bologna, Italy.

Engel, B., Navulur, K., Cooper, B. & Hahn, L. 1996 Estimating groundwater vulnerability to nonpoint source pollution from nitrates and pesticides on a regional scale. In: *Application of Geographic Information Systems in Hydrology and Water Resources Management* (K. Kovar & H. P. Nachtnebel, eds), IAHS Press, Institute of Hydrology, Wallingford, UK, pp. 521–526.

Focazio, M. J., Kolpin, D. W., Barnes, K. K., Furlong, E. T., Meyer, M. T., Zaugg, S. D., Barber, L. B. & Thurman, M. E. 2008 A national reconnaissance for pharmaceuticals and other organic wastewater contaminants in the United States – II) untreated drinking water sources. *Science of the Total Environment* **402** (2–3), 201–216.

Foster, S. S. D. 1998 Groundwater recharge and pollution vulnerability of British aquifers: a critical overview. *Geological Society, London, Special Publications* **130** (1), 7–22.

Frind, E. O., Molson, J. W. & Rudolph, D. L. 2006 Well vulnerability: a quantitative approach for source water protection. *Groundwater* **44** (5), 732–742.

Goldscheider, N., Klute, M., Sturm, S. & Hötzl, H. 2000 The PI method – a GIS-based approach to mapping groundwater vulnerability with special consideration of karst aquifers. *Zeitschrift für Angewandte Geologie* **46** (3), 157–166.

Iqbal, J., Gorai, A. K., Tirkey, P. & Pathak, G. 2012 Approaches to groundwater vulnerability to pollution: a literature review. *Asian Journal of Water, Environment and Pollution* **9** (1), 105–115.

Khakhar, M., Ruparelia, J. P. & Vyas, A. 2017 Assessing groundwater vulnerability using GIS-based DRASTIC model for Ahmedabad district, India. *Environmental Earth Sciences* **76** (12), 440.

Khodabakhshi, N., Asadollahfardi, G. & Heidarzadeh, N. 2015 Application of a GIS-based DRASTIC model and groundwater quality index method for evaluation of groundwater vulnerability: a case study, Sefid-Dasht. *Water Science and Technology: Water Supply* **15** (4), 784–792.

Leone, A., Ripa, M. N., Uricchio, V., Deák, J. & Vargay, Z. 2009 Vulnerability and risk evaluation of agricultural nitrogen pollution for Hungary's main aquifer using DRASTIC and GLEAMS models. *Journal of Environmental Management* **90** (10), 2969–2978.

Lobo-Ferreira, J. P. & Cabral, M. 1991 Proposal for an operational definition of vulnerability for the European Community's Atlas of Groundwater Resources. In: *Meeting of the European Institute for Water*, Groundwater Work Group Brussels.

Lodwick, W. A., Monson, W. & Svoboda, L. 1990 Attribute error and sensitivity analysis of map operations in geographical informations systems: suitability analysis. *International Journal of Geographical Information Systems* **4** (4), 413–428.

Machiwal, D., Jha, M. K., Singh, V. P. & Mohan, C. 2018 Assessment and mapping of groundwater vulnerability to pollution: current status and challenges. *Earth-Science Reviews* **185**, 901–927.

McLay, C. D. A., Dragten, R., Sparling, G. & Selvarajah, N. 2001 Predicting groundwater nitrate concentrations in a region of mixed agricultural land use: a comparison of three approaches. *Environmental Pollution* **115** (2), 191–204.

Meeks, Y. J. & Dean, J. D. 1990 Evaluating ground-water vulnerability to pesticides. *Journal of Water Resources Planning and Management* **116** (5), 693–707.

Mehta, V. K., Walter, M. T. & DeGloria, D. S. 2006 *A Simple Water Balance Model*. Technical Report No 5, Cornell University, Ithaca, NY, USA.

Merchant, J. W., Whittemore, D. O., Whistler, J. L., McElwee, C. D. & Woods, J. J. 1987 Groundwater pollution hazard assessment: a GIS approach. In: *Proceedings of the International Geographic Information Systems (IGIS) Symposium, Volume 3*. Association of American Geographers, Washington, DC, USA, pp. 103–115.

Morris, B. L., Lawrence, A. R. L., Chilton, P. J. C., Adams, B., Calow, R. C. & Klinck, B. A. 2003 *Groundwater and Its Susceptibility to Degradation: A Global Assessment of the Problem and Options for Management*. Early Warning and Assessment Report Series RS 03-3, United Nations Environment Programme, Nairobi, Kenya.

Napolitano, P. & Fabbri, A. G. 1996 Single-parameter sensitivity analysis for aquifer vulnerability assessment using DRASTIC and SINTACS. In: *Application of Geographic Information Systems in Hydrology and Water Resources Management* (K. Kovar & H. P. Nachtnebel, eds), IAHS Press, Institute of Hydrology, Wallingford, UK, pp. 559–566.

Narendra, K. & Rao, K. N. 2006 Morphometry of the Meghadrigedda watershed, Visakhapatnam district, Andhra Pradesh using GIS and Resourcesat data. *Journal of the Indian Society of Remote Sensing* **34** (2), 101–110.

National Research Council 1993 *Ground Water Vulnerability Assessment: Predicting Relative Contamination Potential under Conditions of Uncertainty*. National Academies Press, Washington, DC, USA.

Neshat, A., Pradhan, B., Pirasteh, S. & Shafri, H. Z. M. 2014a Estimating groundwater vulnerability to pollution using a modified DRASTIC model in the Kerman agricultural area, Iran. *Environmental Earth Sciences* **71** (7), 3119–3131.

Neshat, A., Pradhan, B. & Dadras, M. 2014b Groundwater vulnerability assessment using an improved DRASTIC method in GIS. *Resources, Conservation and Recycling* **86**, 74–86.

Neukum, C. & Azzam, R. 2009 Quantitative assessment of intrinsic groundwater vulnerability to contamination using numerical simulations. *Science of the Total Environment* **408** (2), 245–254.

Ouedraogo, I., Defourny, P. & Vanclooster, M. 2016 Mapping the groundwater vulnerability for pollution at the pan African scale. *Science of the Total Environment* **544**, 939–953.

Pacheco, F. A. L., Pires, L. M. G. R., Santos, R. M. B. & Sanchez Fernandes, L. F. 2015 Factor weighting in DRASTIC modeling. *Science of the Total Environment* **505**, 474–486.

Panagopoulos, G. P., Antonakos, A. K. & Lambrakis, N. J. 2006 Optimization of the DRASTIC method for groundwater vulnerability assessment via the use of simple statistical methods and GIS. *Hydrogeology Journal* **14** (6), 894–911.

Piscopo, G. 2001 *Groundwater Vulnerability Map Explanatory Notes – Castlereagh Catchment*. NSW Department of Land and Water Conservation, Parramatta, NSW, Australia.

Rosen, L. 1994 A study of the DRASTIC methodology with emphasis on Swedish conditions. *Groundwater* **32** (2), 278–285.

Shirazi, S. M., Imran, H. M., Akib, S., Yusop, Z. & Harun, Z. B. 2013 Groundwater vulnerability assessment in the Melaka State of Malaysia using DRASTIC and GIS techniques. *Environmental Earth Sciences* **70** (5), 2293–2304.

Soutter, M. & Pannatier, Y. 1996 Groundwater vulnerability to pesticide contamination on a regional scale. *Journal of Environmental Quality* **25** (3), 439–444.

Stempvoort, D. V., Ewert, L. & Wassenaar, L. 1993 Aquifer vulnerability index: a GIS-compatible method for groundwater vulnerability mapping. *Canadian Water Resources Journal* **18** (1), 25–37.

Teso, R. R., Poe, M. P., Younglove, T. & McCool, P. M. 1996 Use of logistic regression and GIS modeling to predict groundwater vulnerability to pesticides. *Journal of Environmental Quality* **25** (3), 425–432.

Vijayakumar, C. R., Balasubramani, D. P. & Azamathulla, H. M. 2022 Assessment of groundwater quality and human health risk associated with chromium exposure in the industrial area of Ranipet, Tamil Nadu, India. *Journal of Water, Sanitation and Hygiene for Development* **12** (1), 58–67.

Wei, A., Bi, P., Guo, J., Lu, S. & Li, D. 2021 Modified DRASTIC model for groundwater vulnerability to nitrate contamination in the Dagujia river basin, China. *Water Supply* **21** (4), 1793–1805.

Worrall, F. & Kolpin, D. W. 2004 Aquifer vulnerability to pesticide pollution – combining soil, land-use and aquifer properties with molecular descriptors. *Journal of Hydrology* **293** (1–4), 191–204.

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