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Estimating the vulnerability of groundwater resources to diffuse pollution in highlands areas: review of the literature and critical analysis (highlands of Cameroon)

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ABSTRACT

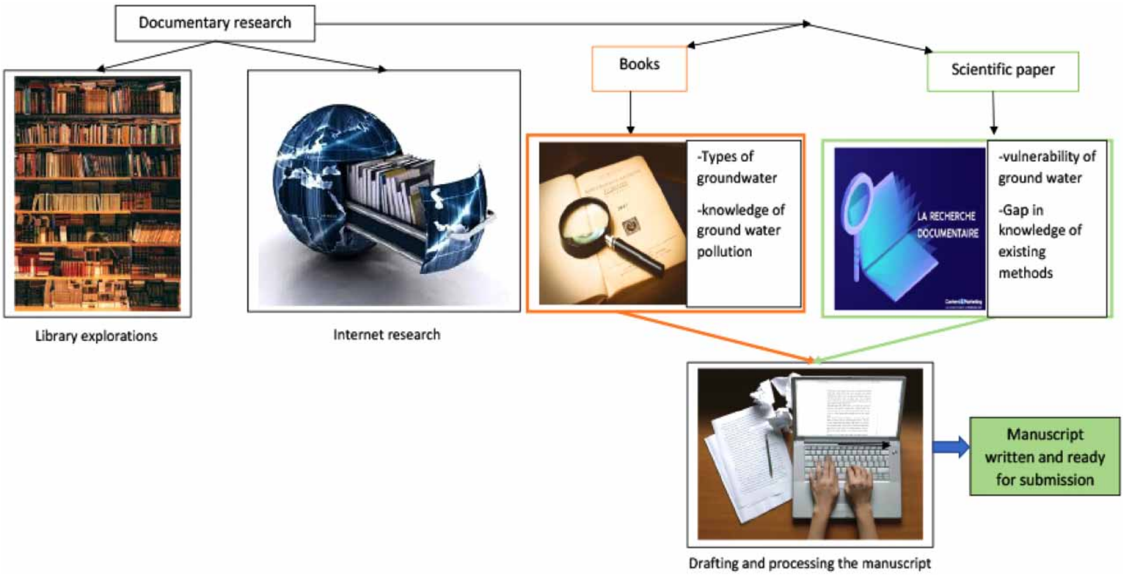
Groundwater is a major resource for drinking water, especially in developing countries, where it is less expensive to treat than surface water. Today, the resource is highly susceptible to pollution, particularly as a result of human activity. This review was based on a literature review and critical analysis of models for estimating the groundwater vulnerability. The results show that the deepest porous aquifers are the least susceptible to pollution, whereas those in karstic and fissured environments are susceptible, whatever their depth. Pollution usually arises from human activity. Critical analysis of the literature shows that existing methods are developed in specific environmental contexts. Given the variability of factors in space and time, these methods do not take the intrinsic realities of all natural settings into account adequately and are not perfectly applicable in all environments. This highlights the need to develop appropriate models for each environment, such as that of the highlands in countries such as Cameroon.

Key words: documentary exploration, groundwater, highlands pollution, vulnerability

HIGHLIGHTS

- The deepest porous aquifers are less susceptible to pollution than karstic and fissured aquifers.
- Existing methods are developed in specific environmental contexts, to solve given problems.
- The variability of factors in space and time means that pre-existing methods are not suitably valid in all natural settings.

GRAPHICAL ABSTRACT



INTRODUCTION

One-third of humanity lives off groundwater for its daily needs, and 99% of planet's accessible freshwater is found in aquifers (FAO 2016). The quality of these waters is declining worldwide, mainly due to human activity, urbanization, land use change, agriculture, and rising living standards (Nguedia Djatsa *et al.* 2022; Nguedia *et al.* 2023). In agricultural areas, the problem arises because fertilizers and plant protection products can reach aquifers and then contaminate them for many years. Potential sources of pollution that can damage groundwater in urban areas include construction sites, vehicular traffic, commercial and industrial activities, polluted areas, and waste and wastewater management (Ducommun 2010).

In Africa and Asia, there are still areas where groundwater vulnerable to pollution is consumed. As this susceptibility is linked to many parameters, there is a range of assessment methods (Mba *et al.* 2023). These can be highly complex and costly, or simplified, each designed to assess vulnerability in environments that may vary in space and time. There is no guarantee that a method developed in a different natural setting will be valid in the geomorphology of high plateaus, mountains, and hills. Because of this, a literature review was the guiding method for clarifying the notion of vulnerability, the state of knowledge of groundwater, the notion of pollution, and methods for estimating groundwater vulnerability. A critical review showed the indispensability of developing models for each environment, such as the uplands.

VULNERABILITY CONCEPT

The world's freshwater reserves represent 3% of the total volume, fresh groundwater accounting for 33% of that (Marsily 2009). The development of human activity in cities in developing countries suggests that groundwater resources are becoming increasingly vulnerable – e.g., in Cameroon's other cities and the country's western highlands. An understanding of intrinsic versus specific vulnerability is important in this context.

According to Vrba & Zaporozec .(1994), vulnerability is an intrinsic property of a groundwater system that depends on its sensitivity to human impacts. Allier *et al.* (2008) note that vulnerability is the 'failure of groundwater to protect or defend itself naturally against pollution threats, depending on local hydrogeological conditions'. In other words, vulnerability represents the natural environment characteristics that determine groundwater's sensitivity to pollution. In this study 'vulnerability' is always associated with groundwater contamination.

Schnebelen *et al.* (2002) acknowledge two types of vulnerability:

- Intrinsic vulnerability represents the natural environment's characteristics that determine the groundwater's sensitivity to pollution from human activity.

- Specific vulnerability defines the groundwater's vulnerability to a particular pollutant or group of pollutants, and takes into account the pollutants' properties and their relationships with the various intrinsic vulnerability components.

The distinction between the two types of vulnerability is important, as they are not generally on the same scale.

Groundwater pollution makes it unsuitable for one of its uses or disrupts the aquatic ecosystem. It can have various sources including phytosanitary products (insecticides, herbicides, fungicides), fertilisers (nitrogenous, etc.), industrial or other accidents (leaking tanks, fires, etc., or lost lorry loads), leaks from sewers, uncontrolled waste dumping, etc. (Margat & Monition 1971; Marsily 2009; Behanzin *et al.* 2021). Pollutants that can reach the water table behave differently as they migrate through the soil and subsoil, and their mobility and persistence in the subsoil are highly variable depending on solubility and ease of biodegradation. These mechanisms depend not only on the nature of the pollutant but also on pH conditions, microbiological activity, humidity, and soil organic matter content (Allier *et al.* 2008). Taking the nature of the pollutants into account when mapping vulnerability would therefore mean drawing up numbers of maps, taking into account the specific characteristics of the different species.

In fact, the concept of intrinsic vulnerability is used. It is independent of the pollutant and describes the groundwater resource's susceptibility to being affected by diffuse or point source surface pollution. Combined with information on human activity, it can be used to assess the risk of groundwater pollution.

A number of intrinsic vulnerability studies include the studies by Dibi *et al.* (2013). There is no standard method for assessing specific vulnerability. Kouakou *et al.* (2022), studying specific vulnerability to nitrate (NO_3) in groundwater in Abidjan, used a combination of a geographic information system (GIS) and multi-criteria analysis, taking the pollutant's properties and relationships with the various intrinsic vulnerability components into account.

GROUNDWATER KNOWLEDGE

Aquifers are hydrologic and hydrodynamic systems characterized by their geometry, area, and depth, as well as the intrinsic properties of the rocks that comprise them, such as lithology, porosity, permeability, fracturing, and homogeneity (Gilli *et al.* 2008). The availability of water in wells between seasons is a subject of debate and disagreement. According to convention, a well should have a positive flow during the rainy season and dry up during the dry season (Barthel *et al.* 2021). However, studies have shown that unconfined aquifers can receive lateral recharge of greater magnitude than vertical recharge during the dry season, allowing wells to have a good flow compared to the rainy season, as observed by Huang *et al.* (2021). This observation has also been made by Nguedia Djatsa *et al.* (2022) in Bafoussam, where water is relatively plentiful during the dry season compared to the rainy season. This is because the soil horizons rest on ignimbritic formations, rich in clay, in the unsaturated zone, which do not favour rapid well recharge, but rather slow recharge that reaches the water table in the dry season. Thus, a well in an unconfined aquifer can be fed either by micro-fractures that drain water, contributing to well recharge, or by low drainage of soils from the watershed.

Pollution

Pollution is often associated with irresponsible and unsustainable practices (Nguedia *et al.* 2023). Companies and individuals often prioritize their short-term economic interests at the expense of the environment, resulting in excessive exploitation of natural resources, greenhouse gas emissions, the production of toxic waste, and natural habitat destruction. Pollution can also be critical because of its potential impact on human health. Exposure to atmospheric pollutants such as fine particles, nitrogen oxides, and volatile organic compounds can lead to respiratory problems, cardiovascular diseases, and even premature deaths. Chemical pollution can, equally, contaminate drinking water sources, with adverse effects on human health (Raimi *et al.* 2022; Tontsa *et al.* 2023).

Vulnerability assessment

Numerous methods for determining groundwater vulnerability have been developed (Gogu & Dassargues 2000). According to Liggett & Talwar (2009), the methods can be divided into three main categories:

- Parametric, with superimposable indices (empirical)
- Physical modelling (numerical mathematics)
- Statistical (predictive)

The choice for producing a vulnerability map depends on the degree of complexity required (Table 1).

Table 1 | Advantages and disadvantages of vulnerability assessment methods

Type	Benefits	Disadvantages	Type of user references	
Empirical parameters	- Reduced costs - Quick - Little need for hydrogeological data - Easily interpretable	- Purely qualitative vulnerability indices - Highly dependent on expert judgement - Frequent differences in estimates between methods (for the same area)	- Administrations and governments - Various experts - Education	Aller *et al.* (1987)
Physical modelling	- Quantified vulnerability indices - Little or no subjective judgement from experts - Can be used to estimate intrinsic and/or specific vulnerability - Based on the physics of underground flow	- A wealth of hydrogeological data - Difficult to use without consulting experts - High costs: labour and software	- Hydrogeology and environmental science experts - Administration and governments	Jeannin (1998)
Statistical forecasting	- Quantified vulnerability indices, with uncertainties – little or no subjective judgement from experts - Direct correlations with field data (actual and potential contamination)	- Specialized: often developed for a single type of contaminant - No 'turnkey' method – difficult to use without consulting experts	- Hydrogeology and environmental science experts - Administrations and governments	Masetti *et al.* (2009)

Parametric methods enable vulnerability indices to be calculated quickly and empirically. They are used frequently and based on a selection of attributes and physical parameters representative of vulnerability (unsaturated zone thickness, type of soil, etc.), which are discretized and classified by the decreasing interval of supposed effect on contamination attenuation (hence increase in vulnerability) (Gogu & Dassargues 2000). There are three sub-systems:

- Matrices – based on a limited number of rigorously selected physical parameters presented in a matrix form. The vulnerability index is estimated quickly and simply, using a multi-parameter table system.
- Combined classified parameters – the physical parameters deemed necessary for estimating vulnerability are distributed over a scale of their estimated influence on attenuation of the potential contamination. The classes are combined using a defined calculation scheme to give a final vulnerability index.
- Point-counts – similar to the combined classified parameter system, with a weighting factor for each parameter, according to its effectiveness in mitigating potential contamination. Final index values are obtained by the weighted parameter value sum.

Index mapping methods with criteria weighting (point count system models) are relevant because they take the relative importance of each criterion into account linked to the water table's vulnerability. They are also widely recognized and used (Vrba & Zaporozec 1994; Gogu & Dassargues 2000; Murat 2000; Doerfliger *et al.* 2009; Mohamed *et al.* 2012; Mfonka *et al.* 2019; Chakraborty *et al.* 2022). The most widely recognized include PaPRIKa, EPIK, RISK, DISCO, GOD, DRASTIC, SINTACS, AVI, and SI, and assessment commonly takes the criteria described in Table 2 into account (Bézèlgues *et al.* 2002).

The most widely recognized methods for estimating groundwater vulnerability depend on the environment in which the aquifer stands.

EPIK

The first method is dedicated to karstic aquifers (Doerfliger *et al.* 2009), and it is based on four criteria: epikarst, protective cover (soil), infiltration conditions, and karst network. It was developed to delimit water catchment protection perimeters in accordance with Swiss legislation. An advantage is that it reflects the sensitivity of groundwater to any type of contaminant. It has been used in the Swiss Jura (Doerfliger & Zwahlen 1998).

Table 2 | Criteria for estimating vulnerability using the parametric method

Intrinsic vulnerability			
Soil	**Unsaturated zone (UZ)**	**Saturated zone**	**Specific vulnerability**
Runoff infiltration	Depth of free water table or UZ thickness	Free or confined water table	Land use: forest/natural areas, agriculture/crops (irrigation increases percolation, and drainage reduces it), urbanization/industrial fabric, etc.
Pedology, vertical permeability, and nature and texture of soils	Transfer time; vertical permeability	Residence time depends on the aquifer's hydrodynamic parameters, and the presence or absence, and position of a less-permeable horizon	Presence or absence of a salt wedge
	UZ structure; facies variation, position in vertical profile, texture, organic matter, and clay content	Groundwater/surface water relationship	Sensitive areas: agricultural land, landfill sites, discharges from classified establishments, density of traffic routes, groundwater abstraction, etc.
		Piezometry: changes in the direction of flow depending on the hydrologic cycle period	Soils' dispersive and treatment capacities in face of a specific pollutant
		Aquifer thickness (reserves)	Potential pollutant's behaviour (fixed medium); soluble, insoluble, miscible, immiscible, denser/lighter than water, reactivity with media through which it passes
		Type of hydrogeological system: more or less capacitive and transmissive characteristics. Direction of flow.	Hydrographic network; extension and vulnerability (watercourse quality)

RISKE

This was inspired by EPIK because of its karstic specificity. It is based on five criteria: aquifer rock, infiltration, soil, karstification, and epikarst (Petelet-Giraud *et al.* 2000).

PaPRIKa

This is a multi-criteria method for mapping karstic aquifers' intrinsic vulnerability, and its targets are the resource and catchment. Developed specifically for karstic aquifers, it cannot be applied indiscriminately to all carbonate aquifers (Doerfliger *et al.* 2009). If the carbonate aquifer does not function as karst, it is considered a fractured aquifer and the method does not apply (Doerfliger *et al.* 2009).

DISCO

The aim of DISCO (discontinuities – protective cover) is to define protection zones, taking environmental heterogeneity into account. Three parameters are necessary to assess pollutant transport from any point in the catchment area: the 'discontinuities'; the 'protective cover'; and the 'runoff', which covers surface runoff phenomena before infiltration (slope runoff, and permanent or temporary watercourses). It has been used to estimate groundwater vulnerability in fissured terrain (Mardhel *et al.* 2005).

DRASTIC

DRASTIC was devised in the 1980s by the National Water-Well Association in response to a request from the Environmental Protection Agency (Newell *et al.* 2023) to enable intrinsic vulnerability estimation in relation to hydrogeological conditions in the United States. DRASTIC is based on seven parameters, each of which is assigned a multiplying factor (Dp) (Table 3).

Table 3 | DRASTIC parameter weights

Symbol	Parameter	Properties	Weight
D	Depth to water table	The greater the depth, the longer it takes the contaminant to reach the piezometric surface.	5
R	Refill	Main contaminant transport vehicle. Higher recharge gives greater contamination risk.	4
A	Aquifer lithology	Characterized by saturated soil granulometry. Plays a role in trapping pollutants that can escape due to the soil's absorption capacity. The finer the granulometry, the better the pollutant trapping.	3
S	Soil type	The more soil clay, the greater the heavy metal absorption and groundwater protection.	2
T	Topography	The steeper the land, the greater the runoff and the lower the groundwater contamination.	1
I	Unsaturated zone	Impact determined by ground texture. The more favourable the texture, the greater the pollutant percolation to the piezometric surface.	5
C	Permeability	Higher permeability means faster pollutant transfer	3

DRASTIC is most widely used in Africa, particularly in Cameroon. Ake *et al.* (2010) used it to study intrinsic vulnerability to nitrate pollution (NO_3) in the loose ground of the Bonoua aquifer (south-east of Côte d'Ivoire), where three vulnerability classes (medium, high, and very high) were identified. It has also been applied to assess vulnerability in fissured terrain. In the western Cameroon highlands, DRASTIC has been used in Dschang and Foumban by Mba *et al.* (2019) and Mfonka *et al.* (2019). Although designed for loose formations in agricultural areas, the method has had to be applied in towns, as in the works of Yu *et al.* (2022), Gintamo (2022), Saravanan *et al.* (2023).

GOD

This is an empirical method devised in 1987 by Foster. Its name comes from the acronym: *G*roundwater occurrence, *O*verall aquifer class (aquifer characteristics in terms of lithology and porosity), *D*epth to water table. Like DRASTIC, it has been used in a number of studies (Djenadi & Djerroud 2018).

GALDIT

Analysing aquifer vulnerability to saline intrusion is a special case of both specific and intrinsic vulnerability. Both salinization and intrinsic vulnerability criteria must be taken into account. In this sense, it is a specific vulnerability. In terms of index mapping, GALDIT is dedicated to coastal aquifer vulnerability to saline intrusion (Doerfliger 2011). GALDIT uses six parameters:

- Type of aquifer: confined or unconfined
- Depth to water table below sea level
- Aquifer hydraulic conductivity
- Distance from shore
- Impact of existing saline intrusion in the area
- Aquifer thickness

The method is used to assess groundwater vulnerability in coastal areas, as in the study by Amarni *et al.* (2020) who worked in coastal Cherchell aquifer, Central Algeria.

Susceptibility index

Susceptibility index (SI) is a specific vertical vulnerability assessment method, developed by Ribeiro Aydi (2018), which takes into account agricultural pollutants, particularly nitrate and pesticides. Five parameters are used, the first four parameters are identical to those used in DRASTIC – D: depth to water table; R: effective aquifer recharge; A: lithology; T: topographic slope. The fifth parameter is land use (OS – Table 4), with a score of 0–100 assigned to each land use class. SI has been used by several authors as it gives the specific vulnerability via OS (Ake *et al.* 2010; Attafi 2018).

Table 4 | SI land use classes

Land cover (CORINE Land Cover classification)	Land use factor, LU
Landfill and dumps, mines	100
Irrigated perimeters, rice fields	90
Quarries, shipyards	80
Covered artificial areas, green areas	75
Permanent crops (vineyards, orchards, olive trees, etc.)	70
Pasture and agroforestry	50
Aquatic environments (marsh, saline, etc.)	50
Forests and semi-natural areas	0

SINTACS

SINTACS was developed in the 1990s (Petelet-Giraud *et al.* 2000) and is a version of DRASTIC adapted to Mediterranean conditions. The method is specific, compared to DRASTIC, because it suggests five vulnerability scenarios, from 'normal' to 'severe', relating to different aquifer types.

Some authors combine methods to enable comparison to determine the most suitable. DRASTIC is considered complex in most cases but is thought suitable compared to other conventional groundwater vulnerability assessment methods – e.g., Momejian *et al.* (2019). Recently, Luo *et al.* (2023) estimated groundwater vulnerability by comparing versions of DRASTIC and GALDIT adapted using hierarchical process analysis (AHP).

The methods are often modified, too. DRASTIC is generally the most suitable, given its complexity and the slightly larger number of parameters used. For example, Bouchnan (2015) used the modified F-DRASTIC method to estimate fractured aquifer vulnerability in Morocco, introducing a fracturing index 'F' as the eighth parameter. Sener & Davraz (2013) used an AHP multi-criteria analysis to adapt DRASTIC to assess groundwater vulnerability in the Egirdir basin of Lake Isparta, Turkey. This made it possible to obtain new weights and add two parameters – lineaments and land cover – to DRASTIC. Other authors have relied on modifying the DRASTIC's factor weightings using the AHP method. Examples include the studies by Saravanan *et al.* (2023) in Cuddalore, India, and by Saravanan *et al.* (2023) assessing the vulnerability of unconfined groundwater in Thoothukudi, Tamil Nadu, India.

Some authors find DRASTIC complex and select its important factors to create a modified version with reduced parameters. An example is the DRIST method (Drias & Tubal 2015), based solely on parameters relating to recharge, the soil (slope and lithologic nature), and the unsaturated zone (nature and thickness). The authors consider that only these parameters are involved in pollution transmission to the water table, and assign the same weights, scores, and classes to them as those defined for DRASTIC.

Critical analysis of vulnerability assessment methods

Vulnerability mapping is a decision-making tool for land use planning and water resource protection, and presupposes the validity of the maps available. Vulnerability assessment parameters, however, tend to vary over time, and this approach is also limited by the temporal variability of other human activities, such as irrigation and exploitation. Consequently, the study of vulnerability dynamics as affected by the parameters' temporal variability is also important, enabling vulnerability evolution to be monitored, while identifying the key factors for groundwater resource management and protection.

The study area – the Cameroon Highlands – is not in a karstic zone, so methods like PaPRIKa, EPIK, and RISK, developed for karstic environments (Doerfliger *et al.* 2009), are not suitable. DISCO (discontinuities – protective cover) aims to define protection zones and characterise the vulnerability of a highly heterogeneous fissured discontinuous aquifer, taking into account the geological and hydrogeological factors conditioning the fissured aquifer's functioning (Mardhel *et al.* 2005). For example, Dibi *et al.* (2013) working in Côte d'Ivoire on granular aquifers used DRASTIC and SINTACS, each with seven vulnerability parameters. (An alterite comprises superficial, usually unconsolidated, material formed *in situ* by the physico-chemical alteration of previous lithologies, without notable pedological transformations.)

For this study, the margins of error for the map veracity rates were about 17 and 18% for DRASTIC and SINTACS, respectively. The values obtained make it possible to revise the parameter scores and weights in DRASTIC and SINTACS.

Saida (2013) working in the Mitidja (northern Algeria) on groundwater vulnerability to nitrate showed that by applying the standard DRASTIC method coupled with GIS, areas with high nitrate levels were superimposed on areas of high vulnerability. Unlike the study area – low hills flattened by erosion, and flat-bottomed valleys through which permanent and intermittent watercourses flow (Regnoult 1986) –the Mitidja is a vast plain for which the standard DRASTIC method should be modified, as topographic effects on vulnerability will not be as representative because of the non-uniform upland geomorphology.

The comparative study of methods for estimating the intrinsic vulnerability of granular aquifers to pollution in the Laurentian Piedmont by Murat (2000) demonstrates that DRASTIC was not designed for all environments, as it was developed in the context of nitrate pollution in the United States. Each environment has its own properties, which is why Ducommun (2010) specifies that adapted intrinsic vulnerability for urban areas should spatialize the impact of urban elements on the intrinsic vulnerability index values. A map of anthropogenic processes affecting recharge and a spatialization of risks in urban areas should also be produced. Mohamed *et al.* (2012) evaluated groundwater vulnerability to pollution in Meknes, Morocco, based on indexing and environmental factor weighting (DRASTIC and GOD) and showed that DRASTIC is better for assessing groundwater vulnerability to pollution. Since Meknes is a densely populated city, the method used does not take land use into account. Mfonka *et al.* (2019) studied the Foubam aquifers on the Western Noun Plain using piezometric monitoring coupled with DRASTIC and showed, through statistical tests, that the water table's depth and the unsaturated zone's impact both have significant impacts on estimating vulnerability.

Over time, authors like Saranya *et al.* (2021) and Saravanan *et al.* (2023) have learned to understand and adapt the weights and scores of DRASTIC's factors to their study contexts, using the AHP method. The problems of factor redundancy persist, however, making the model more complex and costly. Another, previous approach for adequate groundwater vulnerability estimation is that authors change (increase/reduce) the number of parameters, as well as adapting the model's weights. Adding factors makes the model more complex with an increase in criteria redundancy, making it more costly. Those who reduce the criteria do not usually add new ones – e.g., Sener & Davraz (2013) and Gintamo (2022) – who opt for simplified models that reflect their natural frameworks' specificities better. Indeed, any work based on DRASTIC but outside its context would be limited by the fact that the factors remain those of the natural framework for which it was developed. It would be appropriate for each study, in fact, to develop a groundwater vulnerability estimating model that takes the intrinsic factors of the natural framework into account.

CONCLUSIONS

The study's aim was to present the notions of vulnerability and pollution, as well as methods for estimating groundwater vulnerability. Numerous methods for estimating vulnerability exist that do not fit in with all natural settings – e.g., upland areas. Critical analysis of existing methods and their applicability to uplands revealed that the spatio-temporal variability of the criteria generally considered is a factor in their lack of validity in all types of environments, specifically uplands.

DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Ake, G. E., Kouadio, H. E., Dongo, K., Dibi, B., Kouame, F. K. & Biemi, J. 2010 Application des méthodes DRASTIC et SI pour l'étude de la vulnérabilité à la pollution par les nitrates (N03) de la nappe de Bonoua (Sud-Est de la Côte d'Ivoire). (Application of DRASTIC and SI methods to study vulnerability to nitrate (N03) pollution of the Bonoua aquifer (south-east Ivory Coast). *Int. J. Biol. Chem. Sci.* **4**(5), 1676–1692. ISSN 1991-8631.

Aller, L., Bennet, T., Lehr, J. H., Etty, R. & Hackett, G. 1987 DRASTIC: a standardized system to evaluate ground water pollution potential using hydrogeologic settings. U.S EPA-600/2-87-035, 455 p.

Allier, D., Vittecoq, B. & Mardhel, V. 2008 Évaluation de la vulnérabilité intrinsèque des eaux souterraines de la Martinique. Étude réalisée dans le cadre des projets de Service public du BRGM. (Assessment of the intrinsic vulnerability of groundwater in Martinique. Study carried out as part of BRGM's public service projects) BRGM/RP-56283-FR. 81 pp.
Amarni, N., Fernane, L., Naili, M., Lounas, R. & Belkessa, R. 2020 Mapping of the vulnerability to marine intrusion "in coastal Cherchell aquifer, Central Algeria" using the GALDIT method. *Groundwater for Sustainable Development* **11**, 100481.
Attafi, S. 2018 *Évaluation de la vulnérabilité des eaux souterraines à la pollution à l'aide d'une méthode spécifique SI: application sur l'aquifère alluvial du Haut Cheliff. Mémoire Faculté des Sciences, Université Djilali Bounaama-Khemis-Miliana en Algérie. (Evaluation of the Vulnerability of Groundwater to Pollution Using a Specific SI Method: Application to the Alluvial Aquifer of the Haut Cheliff). Dissertation*, Faculty of Science, Djilali Bounaama University, Khemis-Miliana, Algeria.
Aydi, A. 2018 Evaluation of groundwater vulnerability to pollution using a GIS-based multi-criteria decision analysis. *Groundwater for Sustainable Development* **7**, 204–211.
Barthel, R., Stangefelt, M., Giese, M., Nygren, M., Seftigen, K. & Chen, D. 2021 Current understanding of groundwater recharge and groundwater drought in Sweden compared to countries with similar geology and climate. *Geografiska Annaler: Series A, Physical Geography* **103**(4), 323–345.
Behanzin, P., Dossou, G., Hekpazo, P., Saïnou, J., Fanou, G. & Adech, G. 2021 Aspects socioéconomiques et sanitaires de l'occupation de la berge lagunaire de Kpankpan dans la ville de Cotonou au Bénin. (Socio-economic and sanitary aspects of the occupation of the Kpankpan lagoon bank in the city of Cotonou in Benin.).
Bézèlgues, S., Garets, E., Mardhel, V. & Dörfliger, N. 2002 Cartographie de la vulnérabilité de Grand-Terre et de Marie-Galatie (Guadeloupe). Phase 1: Méthodologie de détermination de la vulnérabilité. Rapport BRGM-51783-FR. Journal of Geographic Information System, Vol.6 No.1. (Mapping the vulnerability of Grand-Terre and Marie-Galatie (Guadeloupe). Phase 1: Methodology for determining vulnerability. Report BRGM-51783-FR. Journal of Geographic Information System, Vol.6 No.1.).
Bouchnan, R. 2015 *Vulnérabilité des aquifères fracturés : méthode F-DRASTIC et aspect dynamique. Applications aux aquifères d'Angad et de Bou-Areg (Maroc). Thèse de doctorat faculté des sciences et techniques Tanger (Maroc). (Vulnerability of fractured aquifers: F-DRASTIC method and dynamic aspect. Applications to the Angad and Bou-Areg Aquifers (Morocco). PhD Thesis*, Faculty of Science and Technology, Tangiers, Morocco, p. 176.
Chakraborty, B., Roy, S., Bera, A., Adhikary, P. P., Bera, B., Sengupta, D. & Shit, P. K. 2022 Groundwater vulnerability assessment using GIS-based DRASTIC model in the upper catchment of Dwarakeshwar river basin, West Bengal, India. *Environmental Earth Sciences* **81**(1), 1–15.
Dibi, B., Kouassi, K. L., Kouamé, K. I., Konan, K. S., Soumahoro, M., Konan-waidhet, A. B. & Gnakri, D. 2013 Évaluation de la vulnérabilité à la pollution des aquifers des formations altérités à partir des méthodes DRASTIC et SYNTACS: Cas de la ville de M'bahiakro, Centre de la Côte d'Ivoire. ISSN 2028-9324 Vol. 2, pp. 464–476 (Evaluation of the vulnerability to pollution of aquifers in altered formations using DRASTIC and SYNTACS methods: Case of the town of M'bahiakro, Central Ivory Coast. ISSN 2028-9324 Vol. 2, pp. 464–476).
Djenadi, H. & Djerroud, Y. 2018 Étude de la vulnérabilité à la pollution de la zone de Boulimat par la méthode GOD. Mémoire Faculté des Sciences Université A. MIRA-Béjaia Algeria. (Study of the vulnerability to pollution of the Boulimat area using the GOD method. Mémoire Faculté des Sciences Université A. MIRA-Béjaia Algeria.).
Doerfliger, N. 2011 Montée du niveau marin induite par le changement climatique, conséquences sur l'intrusion saline dans les aquifères côtiers en métropole. (Sea level rise induced by climate change: consequences on saline intrusion in coastal aquifers in Metropolitan France. Interim report, BRGM.).
Doerfliger, N. & Zwahlen, F. 1998 *Practical Guide: Groundwater Vulnerability Mapping in Karstic Regions (EPIK)*. Swiss Agency for the Environment, Forests and Landscape (SAEFL), Bern.
Doerfliger, N., Plagnes, V., Kavouri, K. & Gouin, J. 2009 Cartographie de la vulnérabilité intrinsèque des aquifères karstiques. Guide méthodologique de la méthode PaPRIKa. Bureau de Recherches Géologiques et Minières (BRGM). Orléans, France. (Mapping the intrinsic vulnerability of karstic aquifers. Methodological guide to the PaPRIKa method. Bureau de Recherches Géologiques et Minières (BRGM). Orléans, France.) 105 pp.
Drias, T. & Tubal, A. C. 2015 Cartographie de la vulnérabilité a la pollution de la nappe alluviale de tebessa-morsott (bassin versant de l'oued ksob) extreme EST Algérien. (Mapping of the vulnerability to pollution of the alluvial aquifer of tebessa-morsott (catchment basin of the wadi ksob) in extreme eastern Algeria). Larhyss Journal, ISSN 1112–3680, No. 22, pp. 35–48.
Ducommun, R. 2010 Estimation et cartographie de la vulnérabilité des eaux souterraines en milieu urbain. (Urban Groundwater Vulnerability Assessment and Mapping). UNINE, Neuchâtel, Switzerland, 310 p.
FAO 2016 Gouvernance des eaux souterraines: Vision globale commune 2030 et Appel à l'action (Joint Global Vision 2030 and Call to Action) 20 p. Consulté le 18 septembre 2018 sur. Available from: https://www.fao.org/publications/card/fr/c/dc247b2d-dbd0-4b22-8dda-2f93bbcba8e2/
Gilli, E., Mangan, C. & Murdry, J. 2008 Hydrogéologie: Objets, méthodes, applications. (Hydrogeology: Objects, methods, applications). 3rd edition on AbeBooks.fr ISBN 10:2100576399 – ISBN Livre.
Gintamo, T. T. 2022 GIS and remote sensing-based integrated modelling of climate and land use change impacts on groundwater quality: Cape Flats Aquifer, South Africa. A thesis submitted in fulfilment of the requirements for the Doctor of Philosophy in Environmental and Water Sciences, Department of Earth Sciences, Faculty of Natural Sciences, University of the Western Cape. 162 p.

Gogu, R. C. & Dassargues, A. 2000 Current trends and future challenges in ground water vulnerability assessment using overlay and index methods. *Environmental Geology* **39**, 549–559.

Huang, X., Ping, J., Leng, W., Yu, Y., Zhang, M. & Zhu, Y. 2021 A study on groundwater recharge in the Anyanghe River alluvial fan, North China Plain, based on hydrochemistry, stable isotopes and tritium. *Hydrogeology Journal* **29**(6), 2149–2170.

Jeannin, P. Y. 1998 *Structure et Comportement Hydraulique des Aquifères Karstiques. (Structure and Hydraulic Behaviour of Karst Aquifers)*. PhD Thesis, University of Neuchâtel, Switzerland, p. 237, Suisse, 237 p.

Kouakou, L. P. M. S., Kouyate, A., Sanou, A., Tigori, M. A., Meite, N., Bohoussou, K. J. P. & Dibi, B. 2022 Evaluation of the physico-chemical quality of drinking water in the city of Daloa (Mid-West of Côte d'Ivoire)–Effects on human health. *Journal of Health and Environmental Research* **8**(3), 186–196.

Liggett, J. E. & Talwar, S. 2009 Groundwater vulnerability assessments and integrated water resource management. *Watershed Management Bulletin* **13**(1), 18–29.

Luo, D., Ma, C., Qiu, Y., Zhang, Z. & Wang, L. 2023 Groundwater vulnerability assessment using AHP-DRASTIC-GALDIT comprehensive model: a case study of Binhai New Area, Tianjin, China. *Environmental Monitoring and Assessment* **195**(2), 268.

Mardhel, V., Pinson, S. & Gravier, A. 2005 Cartographie de la Vulnérabilité intrinsèque des eaux souterraines en région Nord–Pas-de-Calais. (Mapping the intrinsic vulnerability of groundwater in the Nord-Pas-de-Calais region.) Study carried out as part of BRGM's public service operations in 2004 - PSP04NPC35, BRGM/RP-54238-EN.

Margat, J. & Monition, L. 1971 Les eaux souterraines, gestion et protection. (Groundwater, management and protection.) Report B.R.G.M 71 sgn 108 hyd. 44 p.

Marsily, G. 2009 L'eau, un trésor en partage, Paris, Dunod. (Water, a shared treasure) Paris, Dunod, 264 p. Available from: https://www.dunod.com (accessed 21 February 2019).

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**(12), 3836–3846.

Mba, F. F., Temgoua, E., Kengne, P. D. & Kamhoua, S. N. 2019 Vulnérabilité des eaux souterraines dans la ville de Dschang. *Int. J. Biol. Chem. Sci.* **13**(5), 39–56.

Mba, F. F., Temgoua, E., Djousse Kanouo, B. M., Tontsa, L., Wowinwo, R. T. & Kamhoua, C. N. 2023 Assessment of the sensitivity of water resources in the intertropical zone: a bibliographical study with perspectives. *Water Supply* **23**(5), 2062–2080.

Mfonka, Z., Ndam Ngoupayou, J. R., Kpoumie, A., Ndjigui, P. D., Zammouri, M., Ngouh, A. N., Mouncherou, O. F., Mfochivé, O. F. & Rakotondrabe, F. 2019 Hydrodynamic and groundwater vulnerability assessment of the shallow aquifer of the Foumban locality (Bamoun plateau, Western-Cameroon). *Arabian Journal of Geosciences* **12**, 1–23. https://doi.org/10.1007/s12517-019-4328-x.

Mohamed, B., Omar, M., Ali, E., Marnik, V., Marie-Paule, K. & Samir, E. 2012 Évaluation de la vulnérabilité des eaux souterraines à la pollution à l'aide des systèmes d'informations géographiques. (Assessing the vulnerability of groundwater to pollution using geographic information systems). *Journal of Hydrocarbons Mines and Environmental Research* **3**(2), 7–13.

Momejian, N., Abou, N. M., Alameddine, I. & El-Fadel, M. 2019 Groundwater vulnerability models assess seawater intrusion. *Environmental Impact Assessment Review* **75**. ISSN 0195-9255. doi:10.1016/j.eiar.2018.10.003.

Murat, V. 2000 Étude comparative des méthodes d'évaluation de la vulnérabilité intrinsèque des aquifères à la pollution: application aux aquifères granulaires du piémont laurentien. Institut National de la Recherche Scientifique (Canada).

Newell, C. J., Stockwell, E. B., Alanis, J., Adamson, D. T., Walker, K. L. & Anderson, R. H. 2023 Determining groundwater recharge for quantifying PFAS mass discharge from unsaturated source zones. *Vadose Zone Journal* **22**(4), e20262.

Nguedia, K. D., Ndongo, B., Ntankouo Njila, R. & Kagou Dongmo, A. 2023 Influence of land use changes on groundwater quality – Bafoussam, West Cameroon. *Water Practice & Technology* **18** (5), 994–1010. doi:10.2166/wpt.2023.077.

Nguedia Djatsa, K., Ndongo, B., Ntankouo Njila, R. & Kagou Dongmo, A. 2022 Hydrodynamic and microbiological characterization of free ground water in the city of Bafoussam, (West Cameroon). *Water Practice and Technology* **17**(6), 1317–1331. https://doi.org/10.2166/wpt.2022.057.

Petelet-Giraud, E., Dörfliger, N. & Crochet, P. 2000 RISKE : méthode d'évaluation multicritère de la vulnérabilité des aquifères karstiques. Application aux systèmes des Fontanilles et Cent-Fonts (Hérault, Sud de la France). (Multi-criteria vulnerability assessment method for karstic aquifers. Application to the Fontanilles and Cent-Fonts systems (Hérault, South of France) Hydrogeology, Final report BRGM/RP-53576- FR 4, 71–88. 140 p.

Raimi, M. O., Ezekwe, C. I., Bowale, A. & Samson, T. K. 2022 Hydrogeochemical and multivariate statistical techniques to trace the sources of ground water contaminants and affecting factors of groundwater pollution in an oil and gas producing wetland in rivers state, Nigeria. *Raimi, O., Ezekwe, C., Bowale, A. and Samson.*

Regnoult, J. M. 1986 Synthèse géologique du Cameroun. Ministère des mines et de l'énergie du Cameroun, Yaoundé. (Geological synthesis of Cameroon. Ministry of Mines and Energy of Cameroon, Yaoundé), 119 p.

Saida, S. 2013 Validité de l'application de la méthode de vulnérabilité DRASTIC à l'étude de la pollution par les nitrates dans la Mitidja (Nord d'Algérie). (Validity of the application of the DRASTIC vulnerability method to the study of nitrate pollution in the Mitidja (northern Algeria). National Institute of Agronomic Research of Algeria (INRAA), 2, Rue des frères Ouaddek BP 200 Hacen Badi, El Harrach.

Saranya, T., Saravanan, S., Jennifer, J. J. & Singh, L. 2021 Assessment of groundwater vulnerability in highly industrialized Noyyal basin using AHP-DRASTIC and Geographic Information System. In *Disaster Resilience and Sustainability*. Elsevier, pp. 151–170. https://dx.doi.org/10.1016/B978-0-323-85195-4.00009-3.

Saravanan, S., Pitchaikani, S., Thambiraja, M., Sathiyamurthi, S., Sivakumar, V., Velusamy, S. & Shanmugamoorthy, M. 2023 Comparative assessment of groundwater vulnerability using GIS-based DRASTIC and DRASTIC-AHP for Thoothukudi District, Tamil Nadu India. *Environmental Monitoring and Assessment* **195**(1), 1–19.

Schnebelen, N., Platel, J. P., Le-Nindre, Y., Beaudry, D., Hoarau, A., Dufour, P. & Benhammouda, S. 2002 Gestion des eaux souterraines en Aquitaine année 5. Opération sectorielle. Protection de la nappe de l'Oligocène en région bordelaise. Rapport BRGM/RP-51178-FR.

Sener, E. & Davraz, A. 2013 Assessment of groundwater vulnerability based on a modified DRASTIC model, GIS and an analytic hierarchy process (AHP) method: The case of Egirdir Lake basin (Isparta, Turkey). *Hydrogeology Journal* **21**(3), 701–714.

Tontsa, L., Temgoua, E., Bertrand, G., Kengni, L., Makaya Mvoubou, M. C., Njueya Kopa, A. & Mba, F. F. 2023 Environmental factors controlling contamination of alternative water supply points in the Lefock semi-urban watershed, Cameroon western highlands. *Environmental Earth Sciences* **82**(1), 1–13. https://doi.org/10.1007/s12665-022-10699-w.

Vrba, J. & Zaporozec, A. 1994 Guidebook on Mapping Groundwater Vulnerability. International Contributions to Hydrogeology, vol. 16. Heinz Heise GmbH, Hannover.

Yu, H., Wu, Q., Zeng, Y., Zheng, L., Xu, L., Liu, S. & Wang, D. 2022 Integrated variable weight model and improved DRASTIC model for groundwater vulnerability assessment in a shallow porous aquifer. *Journal of Hydrology* **608**, 127538.

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