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Robustness of DRASTIC Method for Groundwater Vulnerability Case of Wadi Nil Aquifer in Jijel, NE Algeria

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Abstract - The alluvial water table of Wadi Nil is characterized by an abundance of groundwater, attributed to the high rainfall (1,000 mm/yr on average) of the region, the good permeability of its aquifer (10^{-3} to 10^{-4} m/s), and its significant thickness (35 to 100 m). Its waters are used for drinking water as well as for irrigation. In recent years (2000-2020), significant growth in terms of urban, agricultural, and industrial activities has developed on the plain, and has generated a significant amount of waste and effluents. In order to protect the groundwater resource, a map of the vulnerability of the water table to pollution, intended to guide public policies, has been drawn up. The DRASTIC method is a method chosen for the creation of this map, in view of its efficiency and reliability. The results obtained show that the groundwater consists of three zones: the first zone - of moderate vulnerability - is located in the outcrop areas of the marl formations (central part of the plain); the second - of high vulnerability - occupies most of the plain, composed mainly of the wadi alluvial formations; and finally the third - of very high vulnerability - is located in the downstream part of the groundwater, where the aquifer formations are sandy. The statistical analyses and sensitivity analysis of DRASTIC parameters highlight the importance of the parameters «water depth, recharge, and impact of the vadose zone» in the elaboration of the vulnerability map of the studied area, and show that the approach is relatively robust. Nevertheless, if the "water depth" and "recharge" parameters can be constrained by field measurements, the "impact of vadose zone" parameter appears to be the most delicate, because it is both sensitive and associated with uncertainties.

Keywords: vulnerability, DRASTIC, alluvial groundwater, wadi Nil, Algeria

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Introduction

Background

Groundwater is generally regarded as a preferred supply for drinking water due to its good physico-chemical qualities. In our studied area, these water resources are threatened by various types of pollution (urban, agricultural, and industrial). The infiltration of a pollutant into the groundwater recharge area may lead to groundwater contamination, depending on the continuity of the environment and the power of the water to dissolve the majority of pollutants and to transport these pollutants into the groundwater according to the direction of water flow.

In order to conserve these water resources, a protection plan for each aquifer is essential, after assessing its vulnerability. Margat (1968) was among the first to introduce the notion of groundwater vulnerability to contamination. Since then, several approaches have been used to create aquifer vulnerability assessment maps, such as DRASTIC (Aller *et al.,* 1987), GOD (Foster, 1987), SINTACS (Civita, 1994), and EPIK (Doerfliger and Tache, 1995). According to Gogu and Dassargue (2000), these methods for estimating groundwater vulnerability take into account the evolution of different physical, chemical, and biological parameters in the saturated zone while relying on several methods of indexing and weighting between the different environmental factors affecting vulnerability.

The DRASTIC method is based on three basic assumptions: 1) potential sources of contamination are at the soil surface, 2) potential contaminants reach the aquifer through the effective infiltration mechanism, 3) the nature of the potential contaminants is not considered in the calculation of the index (Boisvert *et al.,* 2008). Vulnerability assessment using the DRASTIC method is based on the study of seven parameters, related to research and aquifer characteristics, coupled with Geographic Information System (GIS) techniques. It allows a good assessment of the sensitivity of water resources and a good spatial delimitation of risk zones.

This method has already been used by several authors across the world, such as Cameron and Pelos (2001), Al Zabet (2002), Murat *et al.* (2003), Jourda *et al.* (2007), Sadkaoui *et al*. (2011), Ben-Daoud *et al.* (2012), Ersoy and Gültekin (2013), and in Algeria Drias and Toubal (2015) and Abdeslam *et al*. (2017)).

Compared to the GOD method, it has produced notably better results in a similar field (Djoudi *et al*., 2019) validated by nitrate contamination measurements.

These various research works have pushed us to opt for the use of the DRASTIC method, which has proven that it is effective and reliable in the determination of areas vulnerable to groundwater pollution, particularly in the alluvial domain.

Geological/Stratigraphical Settings

The alluvial plain of Wadi Nil is located in northeastern Algeria. It is found at 350 km from Algiers and 15 km east of the city of Jijel (Figure 1a). It covers an area of 50 km^2.

From a hydrological point of view, the plain is located in the downstream part of the Wadi Nil watershed (320 km^2). The main Wadi Nil flow and its three tributaries (Wadi Saayoud, Wadi Boukraa, and Wadi Tassift) runs across it (Figure 1b). Two swamps exist in the lowlands: the El-Kennar swamp (Ghdir Ben-Hamza) in the eastern part of the plain and the Rejla swamp in the western part of the plain (Figure 1c).

The studied area has a Mediterranean climate. The average yearly rainfall is approximately 1,000 mm/yr, and the average yearly temperature is about 20°C (according to the National Meteorological Office (ONM), Achouat station (1988-2015).

From a lithological point of view, the Wadi Nil alluvial plain is composed of sedimentary formations from the Miocene up to the Quaternary age, among which are the alluvial deposits of wadis and swamps as well as present dunes (Figure 2). It is bounded to the east by metamorphic formations, aging from the Paleozoic to the Eocene, and mainly composed of shales and mica-schists as well as marl formations of Sahelian age. To the west are marl formations from the Burdigalian age and detrital formations from the Pontian age, whilst to the south it is limited by sandstone and clay formations from the Numidian age as well as detrital formations from the Pontian epoch.

From a hydrogeological point of view, the formations of the plain are generally made up of :

- Permeable formations comprising primarily fine sands (recent dunes) in the coastal area, and coarse elements (gravel, conglomerates,

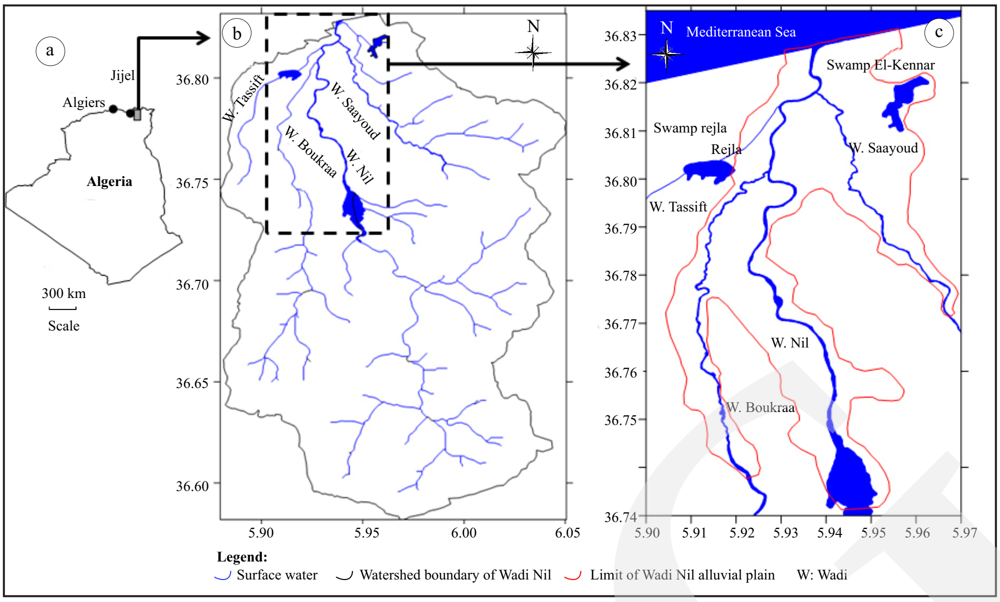

Figure 1. Geographic location of the Wadi Nil alluvial plain. a) Situation of the studied area regarding Algeria; b) Wadi Nil watershed, and c) Wadi Nil alluvial plain.

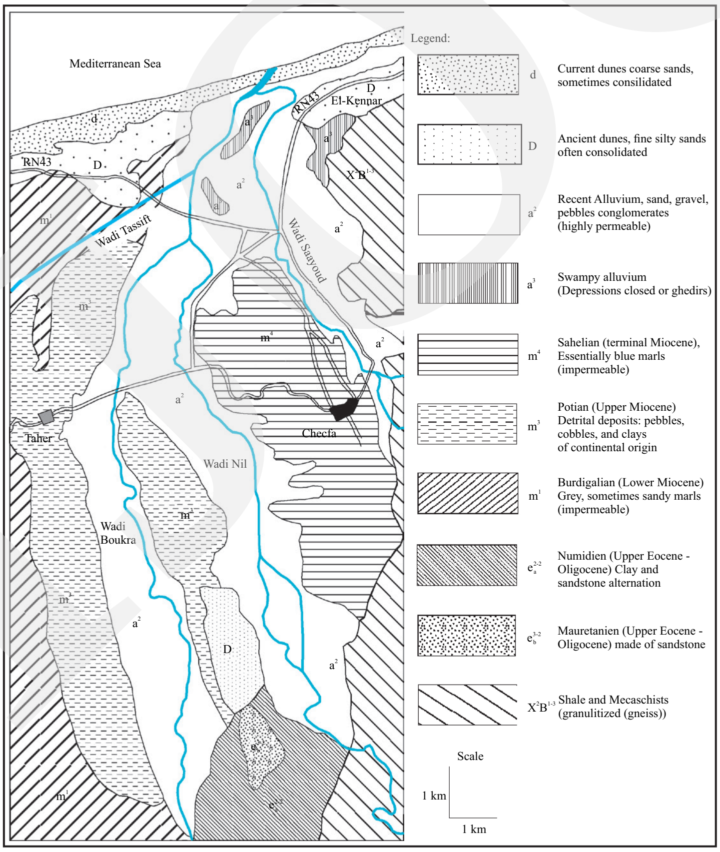

Figure 2. Geological sketch map of the Wadi Nil alluvial plain (extracted from the geological map of El-Milia N°29, Ehrmann, 1928).

and pebbles) along the main wadis (Nil, Saayoud, and Boukraa).

- Semipermeable formations ocurring on both banks of the Boukraa wadi composed of detrital deposits (gravel, pebbles, and clay) from the Pontian epoch.

- Impermeable formations which correspond mainly to marl formations, blue in colour, from the end of the Miocene, the «Sahelian» age, which outcrop in the centre of the plain, between Wadis Saayoud and Nil.

The spatial distribution of the geological formations shows that the upstream section of the alluvial water table of the Wadi Nil is separated by formations from the Miocene, and that each tributary has its own accompanying water table. However, the water table becomes unique and continuous in downstream, after the confluence of the tributaries with the Wadi Nil.

Three lithological sections carried out in the plain (Figure 3), with a NNW-SSE direction (Figure 3, sections 1 and 3) and a NNE-SSW direction (Figure 3, section 2), based on lithostratigraphic data of various boreholes located in the plain, show that the Wadi Nil alluvial groundwater is vertically composed of a unique aquifer, locally separated by clay lenses that give rise to a shallow water table exploited by wells and a deeper water table exploited by means of boreholes. These lenses make the deep aquifer locally accessible. The two aquifers merge together in the absence of a lens and are hydraulically connected. The permeability of the aquifer ranges from 10^{-3} to 10^{-4} m/s. The thickness of the alluvium increases as it goes downstream, reaching thicknesses of the order of 100 m near the confluence of Wadi Boukraa and Wadi Nil. The substratum is made up of grey plastic marls from the Miocene.

The land use of the Wadi Nil alluvial plain is essentially dominated by an agricultural area, characterized by greenhouse cultivation, that

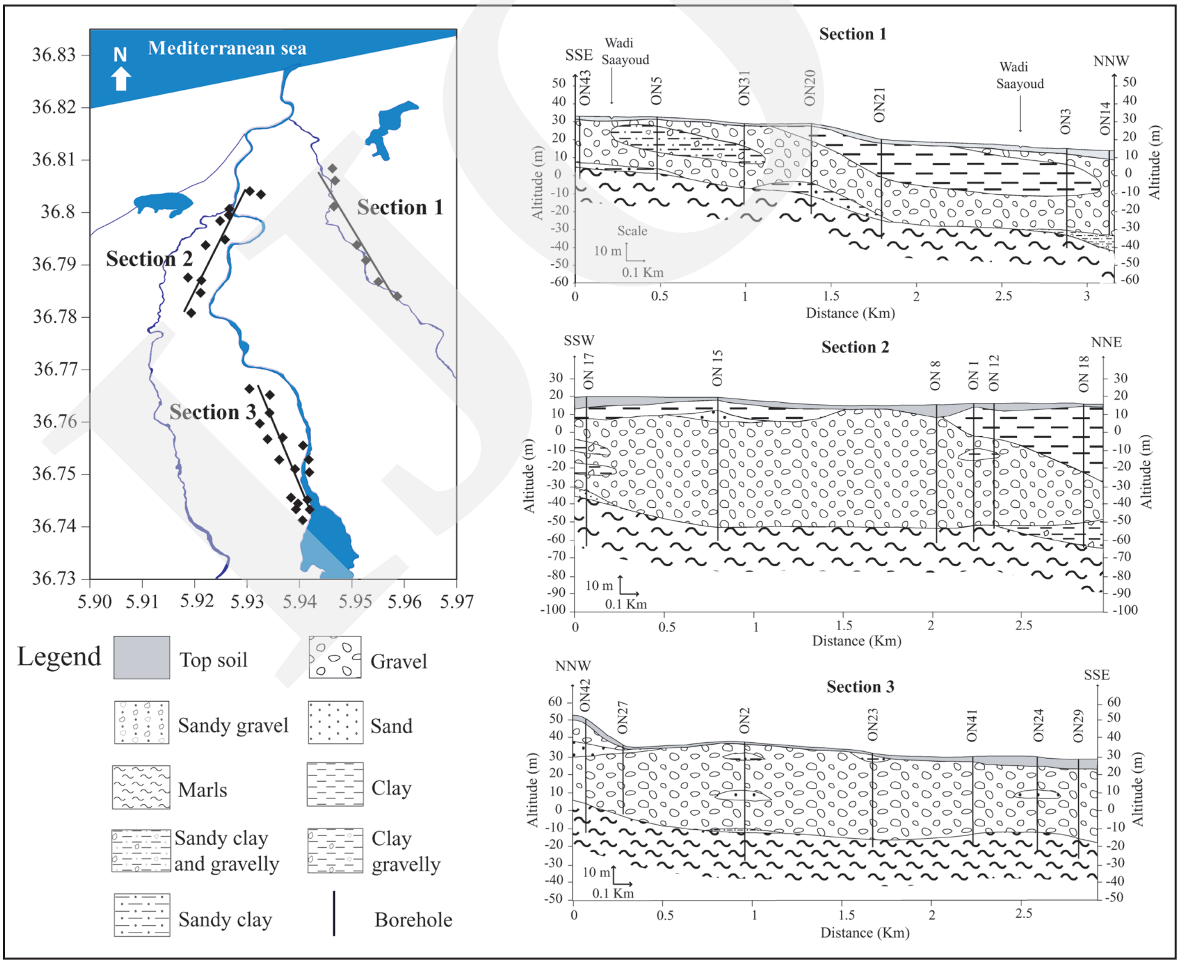

Figure 3. Lithological sections from the stratigraphic logs of the boreholes.

extends along the wadis (Tassift, Boukraa, Nil, and Saayoud), and occupies the majority of the plain (Figure 4), alongside five main urban areas (Taher, Chekfa, El-Kennar, Bazoul, and Djimar). These areas (urban and agricultural) produce several discharges (wastewater, leachate from urban waste, pesticides, herbicides, fertilizers, *etc*.), which pose a risk to the quality of the groundwater.

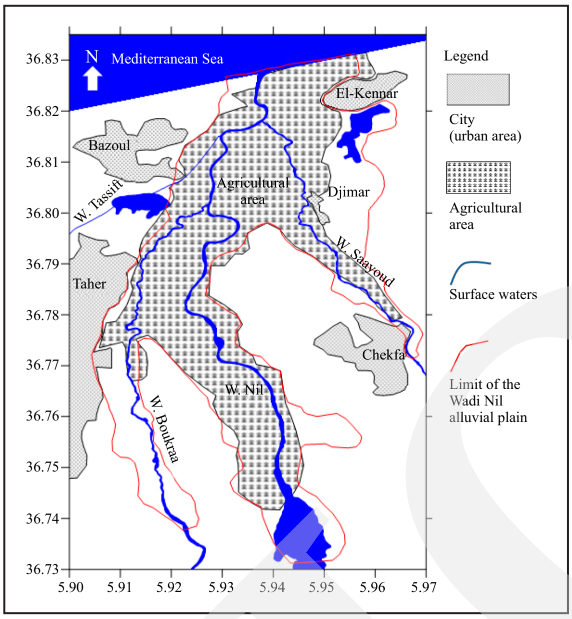

Figure 4. Occupation of the alluvial plain of Wadi Nil (Benessam *et al*., 2015).

Methods and Materials

To carry out the vulnerability map of the Wadi Nil alluvial aquifer, the empirical approach of the DRASTIC method, developed by the US Environmental Protection Agency (EPA) in 1985, was adopted. It is based on seven parameters (Aller *et al*., 1987): Depth of the water table (D), Annual net pure Recharge (R), Aquifer lithology (A), Soil type (S), Topography (T), Impact of the vadose zone (I), and Aquifer hydraulic Conductivity or permeability (C). The impact of the vadose zone is the function of lithology of the unsaturated zone.

Vulnerability indices are calculated by the sum of the partial DRASTIC indices (I) of each parameter.

$$ID = ID + IR + IA + IS + IT + II + IC \quad .... (1)$$

With:
ID: DRASTIC Index;
I (D, R, A, S, T, I, C): Partial DRASTIC Indices of each parameter.

By replacing the partial DRASTIC index by its equation, which corresponds to the sum of the scores of the vulnerability factors multiplied by their respective weights (Table 1), the following equation is obtained:

$$ID=D_rD_W+R_rR_W+A_rA_W+S_rS_W+T_rT_W+I_rI_W+C_rC_W \quad ... (2)$$

with:
ID: DRASTIC index;
(D, R, A, S, T, I, C) r: score or coefficient of the parameter which varies from 1 to 10;
(D, R, A, S, T, I, C) w: weight of the parameter which varies from 1 to 5.

The calculated index represents the degree of vulnerability of the groundwater and changes in proportion to its risk of contamination.

The possible values of the DRASTIC vulnerability index were classified into five intervals (very low, low, medium, high, and very high) of identical amplitudes of 40, with the exception of the first interval which had a value of 44 in order to allow amplitude rounded for the others (Figure 5). The upper and lower values were obtained from the minimum and maximum values of the score for each parameter, calculated using the DRASTIC index formula. It can take a maximum value of 230 (100 %) and a minimum value of 26 (0 %). The definition of the classes based on index values relies on recommendations from Aller *et al*. (1987).

The mapping approach allowed a data base of the physical properties of the studied area to be put together, in order to produce a vulnerability map that represents the spatial distribution and variation of vulnerability indices across the area. Figure 5 illustrates the different steps followed during the elaboration of the vulnerability map

Table 1. Drastic Weighting Factors (Aller *et al*., 1987)

Parameter	Symbol	Interval	Score	Description	Weight
Water Depth (m)	D	0 to 1.5	10	Refering to the depth of the water table of an unconfined aquifer. A deep aquifer implies less risk of contamination. In confined aquifers, the depth of the water table corresponds to the depth of the top of the aquifer.	5
		1.5 to 4.5	9		
		4.5 to 9.0	7		
		9.0 to 15.0	5		
		15.0 to 23.0	3		
		23.0 to 31.0	2		
		> 31	1		
Annual net Recharge (Piscopo, 2001)	R	3 to 5	1	Indicating the amount of water per unit area of land that penetrates the ground surface to reach the water table. Recharging water transports the contaminant vertically to the water table.	4
		5 to 7	3		
		7 to 9	5		
		9 to 11	8		
		11 to 13	10		
Aquifer media (lithology)	A	Massive shale	1 - 3	Refering to the consolidated or unconsolidated medium used as an aquifer. The larger the grain size and the more fractures or openings in an aquifer, the lower the permeability and attenuation capacity, increasing the potential for pollution.	3
		Igneous/metamorphic	2 - 5		
		Igneous/metamorphic altered	3 - 5		
		Till	4 - 6		
		Sandstone, limestone, and shale beds	5 - 9		
		Solid sandstone	4 - 9		
		Massive limestone	4 - 9		
		Sand and gravel	4 - 9		
		Basalt	2 - 10		
		Karstic limestone	9 - 10		
Type of Soil	S	Thin soil or rock	10	Refering to the most altered part of the vadose zone characterized by significant biological activity. Soil has a significant impact on the amount of recharge that can infiltrate the soil.	2
		Gravel	10		
		Sand	9		
		Peat	8		
		Fissured clay	7		
		Sandy loam	6		
		Loam	5		
		Silty loam	4		
		Clay loam	3		
		Black soil	2		
		Clay	1		
Topography (slope) (%)	T	0 – 2	10	Refering to the slope of the land surface. It helps a pollutant to run off or stay on the surface, or to seep in.	1
		2 – 6	9		
		6 – 12	5		
		12 – 18	3		
		>18	1		
Impact of the vadose zone (unsatured zone)	I	Waterproof layer	1	Defined as material in the unsaturated zone above an aquifer forming the containment layers. Used in a confined aquifer as the type of media with the most significant impact.	5
		Silt/clay	3		
		Shale	3		
		Limestone	6		
		Sandstone	6		
		Bedded limestone, sandstone, shale	6		
		Sand and gravel with silt and clay	6		
		Metamorphic rock/igneous rock	4		
		Sand and gravel	8		
		Basalt	9		
		Karstic limestone	10		
Hydraulic Conductivity (m/d)	C	0.04 – 4	1	Refering to the capacity of an aquifer to transmit water by controlling the rate at which groundwater will flow under a given hydraulic gradient.	3
		4 –12	2		
		12 – 29	4		
		29 – 41	6		
		41 – 82	8		
		>82	10		

by compiling geospatial data and calculating DRASTIC indices.

The data used to conduct this study are from the April 2012 season, which corresponds to the high-water period. This campaign was characterized by a large number of measurement points (64 wells, 35 boreholes, and 7 piezometers) spread over the entire plain (Figure 6). The piezometric measurements were carried out using a light probe, resembling SEBA KLL.

Analysis and discussion

Depth of The Water

The depth of the groundwater table in relation to the ground is an important parameter, corresponding to the thickness of the unsaturated zone. It plays a decisive role in the transfer and attenuation of the pollutant before reaching the slick. The greater the depth, the greater the attenuation capacity (Chandoul *et al.,* 2008). The

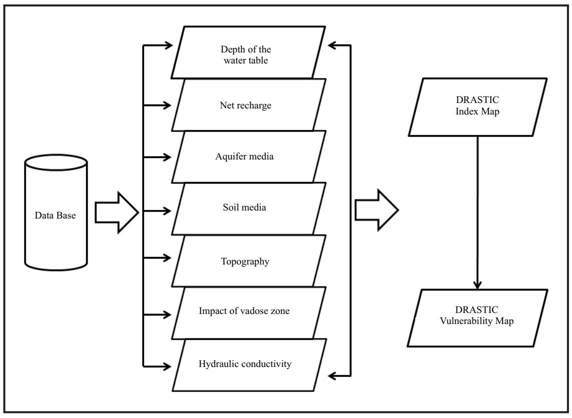

Figure 5. Flowchart showing the elaboration of a vulnerability map using the DRASTIC method.

weight assigned according to the DRASTIC method for this parameter is of the order of 5, whereas the water depth has been classified into seven intervals weighted by a coefficient which varies from 1 to 10.

Calculations of the indices (Dr × Dw) of the depth of the shallow water table (Figure 7a) showed partial DRASTIC indices (ID) varying from 35 to 50, corresponding to water depths ranging from 0 to 5.5 m. In contrast, calculations of the indices of the water depth of the deep water table (Figure 7b) showed partial DRASTIC indices (ID) ranging from 5 to 50, corresponding to water depths extending from 0 to over 31 m.

Net Recharge

Net recharge or effective infiltration is the amount of water that infiltrates per unit area per unit time. It corresponds to the water that infiltrates into the ground, flowing through the unsaturated zone reaching the water table. Net recharge depends on climatic factors and on topography, vegetation cover, and soil permeability. It plays an important role in the transfer of pollutants. The greater the effective infiltration, the greater the vulnerability of the groundwater table.

Net recharge is an important factor in the mitigation of contamination, and is given a weight of 2. The rating system assigned to net recharge is shown in Table 2.

In terms of net recharge, the pollution potential of an area with a confined aquifer is less than that of an unconfined aquifer due to the presence of a containment layer. To quantify recharge in the Wadi Nil alluvial plain, the method proposed by Piscopo *et al*. (2001) was opted for.

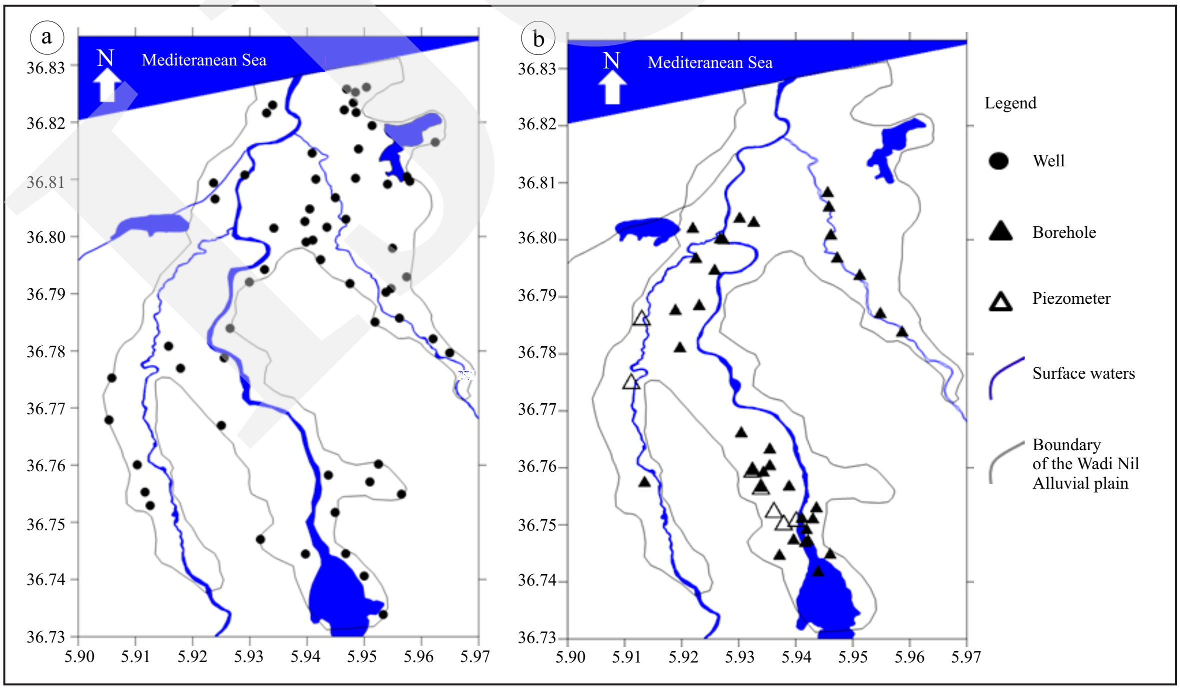

Figure 6. Position of water points. a) Indicates the position of wells (superficial water table) and b) Indicates the position of boreholes and piezometers (deep water table).

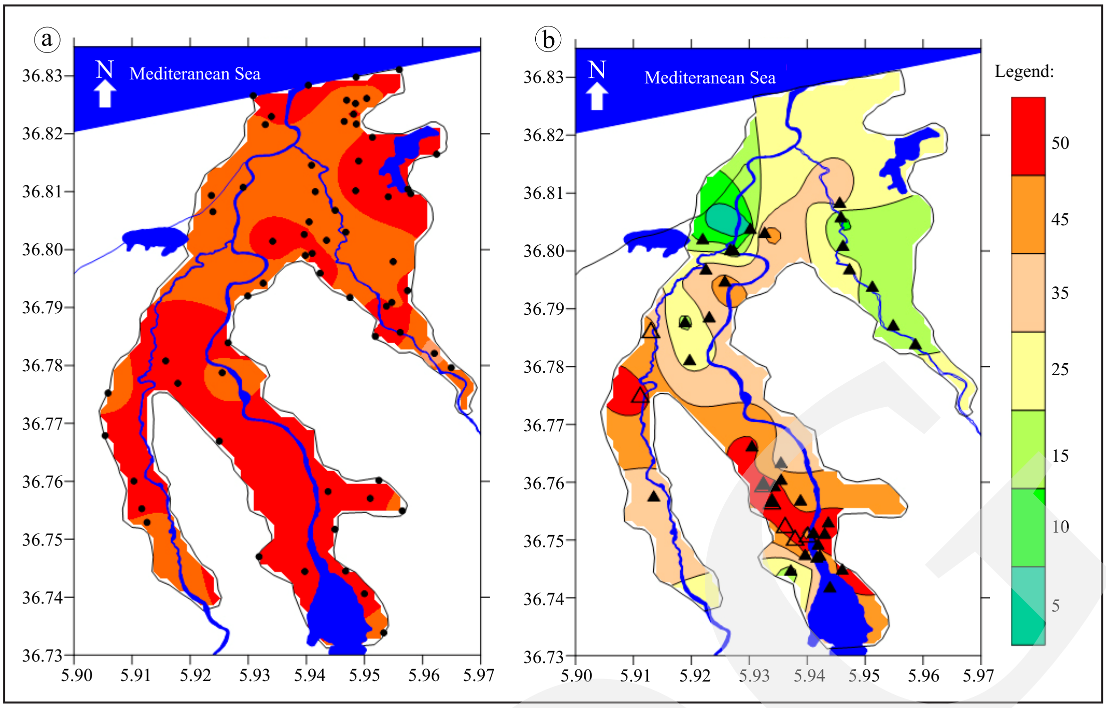

Figure 7. Maps of the vulnerability index (ID) of the groundwater according to the depth of water in the alluvial plain of Wadi Nil. a) Shallow groundwater, b) Deep groundwater.

Table 2. Recharge Ribs and Weightings for The Studied Area (Piscopo, 2001; Al-Adamat *et al*., 2010)

Slope (%)	Range	Rainfall mm/year	Range	Net Recharge	Range
> 33	1	< 500	1	3 - 5	1
10 - 33	2	500 - 700	2	5 - 7	3
2 - 10	3	700 - 850	3	7 - 9	5
< 2	4	> 850	4	9 - 11	8
				11 - 13	10

Soil permeability	Range	Permeability (m/s)	Formation of the studied area
Very slow	1	10^{-8} - 10^{-12}	Clay
Slow	2	10^{-6} - 10^{-8}	Sandy clay, silty, and micaceous
Moderate	3	10^{-4} - 10^{-6}	Vegetable soil, silty, and quartz very fine sand
Medium hight	4	10^{-2} - 10^{-4}	Medium sand, coarse, gravelly
Hight	5	10 - 10^{-2}	Clean gravel

The calculation of the net recharge (Figure 8) shows three distinct partial vulnerability index (RI = Rr x Rw) domains, one covering most of the plain with a partial index (RI) equal to 32, another with a value of 40 covering the northern, and southwestern areas of the plain, and the last partial index equal to 20 (RI) concerns a reduced area located west of the water table.

Aquifer Media

Aquifer media refers to the consolidated or unconsolidated rock that serves as the main aquifer on which the flow and the spread of a contaminant in the saturated zone depends. The identification of the aquifer media was carried out using stratigraphic logs from the various boreholes drilled in the studied area. For geological units, the method proposes ten intervals (or typologies) weighted by a coefficient which varies from 1 to 10; in this case, an assignment with a weight of 3 is obtained according to the DRASTIC method. The aquifer is made up of Quaternary alluvium consisting principally of gravel with semipermeable lenticular passages to

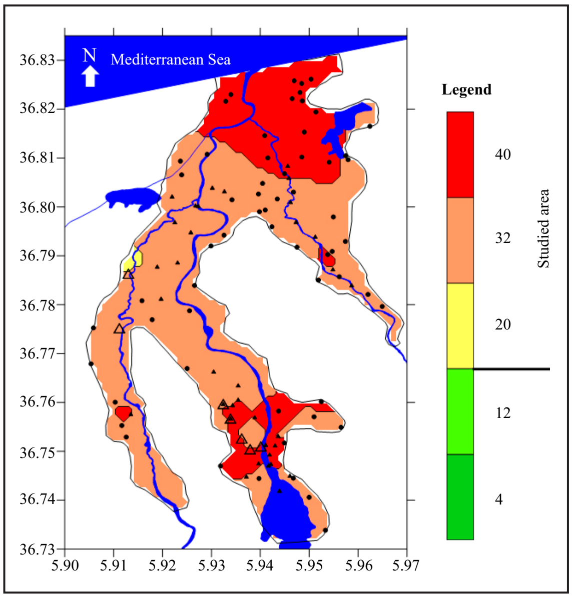

Figure 8. Map of the recharge index (IR) of the Wadi Nil alluvial plain.

the south of the plain and with sands to the north, hence the attribution of the same rating according to the DRASTIC method.

The map of the aquifer media (Figure 9) indicates the existence of a single domain where the permeable material is predominantly sand and gravel with a partial DRASTIC index IA (Ar × Aw) equal to 24.

Soil

It represents the superficial part of the vadose zone and corresponds to about 1 m in depth from the surface. It is characterized by a high biological activity and by a heterogeneity of its mineralogical composition. According to Dibi *et al*. (2013), soil has a direct influence on the amount of water infiltrating through the soil and on the transfer of pollutants. The lower the porosity of the soil, the lower the risk of pollution.

The information gathered from the stratigraphic logs and the geological map made it possible to draw up the soil type map showing that the studied area is characterized by the presence of several textures and dominated by clay, gravel, and sand textures. The DRASTIC method assigns a weight of 2 to this parameter, where elevent classes are weighted by a coefficient varying from 1 to 10.

The soil type calculation has four texture classes. In the central and southern part of the plain, it is dominated by clay loam and sandy loam texture with partial DRASTIC index values (Sr × Sw) of 2 and 6. In the north, it is dominated by a sandy texture mainly corresponding to sand dunes with partial DRASTIC indexes (IS) of 12 and 18 (Figure 10).

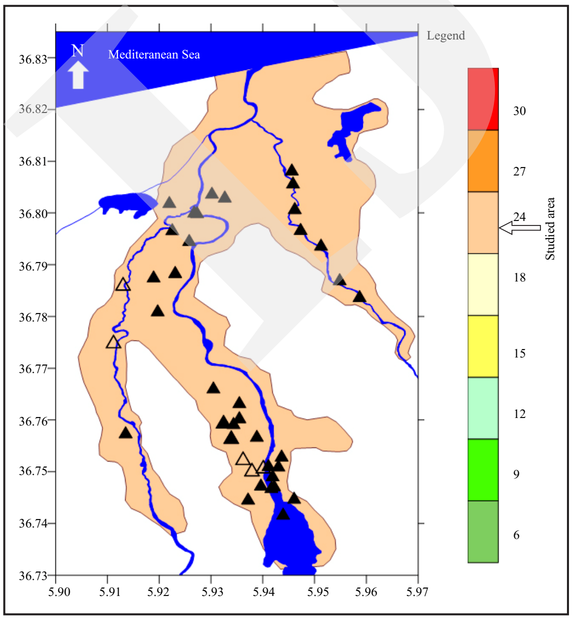

Figure 9. Map of the aquifer media index (IA) of the Wadi Nil alluvial plain.

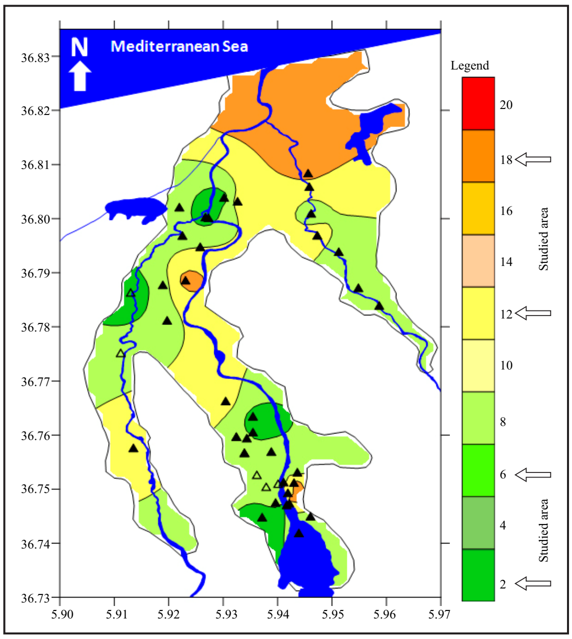

Figure 10. Map of the soil index (IS) of the Wadi Nil alluvial plain.

Topography

The topographic slope reflects the ability of a pollutant to migrate by runoff or infiltration to the water table (Lynchez *et al.*, 1994).

A digital terrain model (DTM) has been established by digitizing contours. The slope values assigned to it are based on the rating system of the DRASTIC method (Table 1). The terrain slope is assigned a very low weight (1) in relation to the other parameters where there are five classes weighted by a coefficient varying from 1 to 10.

The topography of the studied area shows five different intervals ranging from 1 to 10 (Figure 11). The distribution of slopes shows that most of the plain has a relatively low slope of 0 to 6 % with partial DRASTIC index IT (Tr × Tw) scores of 9 or 10. Along the edges near the mountain, where the slopes become steeper, the slopes range from 6 to more than 18 %, with partial DRASTIC indices (IT) ranging from 1 to 5.

Impact of The Vadose Zone

The vadose zone is the unsaturated part of the subsoil between the soil and the saturated zone. The nature of the vadose zone is an important parameter in the protection of the aquifer, since both its thickness and lithology affect the rate of infiltration and dispersion of the pollutant into the aquifer.

The importance of the vadose zone lies in its permeability which is closely linked to the lithological nature and to the granulometry of the soils and its pollutant attenuation capacity. It was assigned a weight of 5 by the DRASTIC method where eleven classes are weighted by coefficients which vary from 1 to 10.

In the Wadi Nil alluvial plain, this parameter was obtained from mechanical sounding data. The results obtained show that the lithology of the unsaturated zone is heterogeneous and essentially made up of fine gravel and sand with some silt or clays.

The calculation elaborated according to the DRASTIC scoring system highlights the distribution of the vadose zone according to five different vulnerability classes with dominance of sand and gravel in the north and the centre of the plain, which have a good permeability favouring the possible infiltration of polluting substances. In this zone, the partial DRASTIC indices I (Ir × Iw) are equal to 30 or 40. Clays occupy the western and south-eastern parts with partial DRASTIC indices ranging from 5 to 20 (Figure 12).

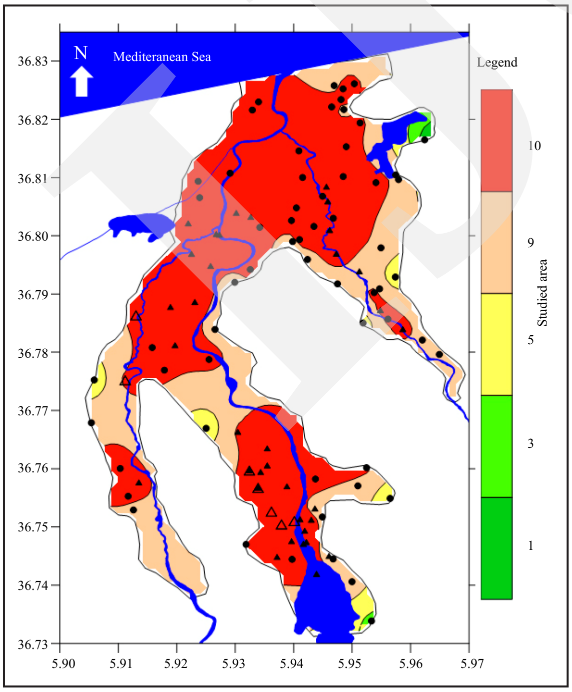

Figure 11. Map of the topographic index (IT) of the Wadi Nil alluvial plain.

Hydraulic Conductivity of The Aquifer

It refers to the speed of water movement in the saturated zone. The DRASTIC method assigned a weight of 3 to hydraulic conductivity or six classes are weighted by a coefficient varying from 1 to 10.

In the case of the deep water table, the hydraulic conductivity values used in this study were obtained from pumping test data from boreholes distributed across the plain. However, for the shallow water table, the permeabilities used represent the geological formations that appear in the first 15 m (Table 2).

The hydraulic conductivity indices for the shallow water table (Figure 13 a) show two partial DRASTIC indices IC (Cr × Cw) which are 3 and 30. The hydraulic conductivity indices for the deep water table (Figure 13b) showed several

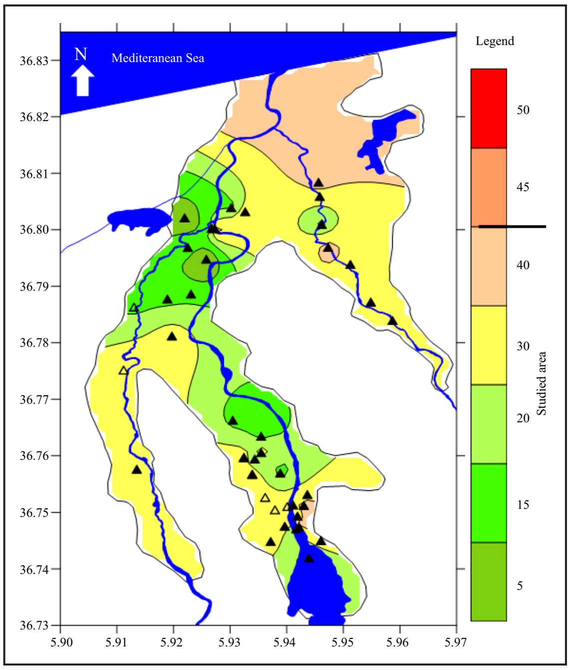

Figure 12. Map of the vadose zone index (II) of the Wadi Nil alluvial plain.

partial DRASTIC indices (ID) ranging from 6 to 30. Low indices correspond to permeabilities between 0.04 to 4 m/day, whereas high indices correspond to permeabilities between 41 to 82 m/day. Low indices are associated to more clayey parts of the alluvium located in the northern, eastern, and southern sections of the plain. High indices are encountered to the south-east of the plain due to the presence of coarser alluvium.

Map of Vulnerability to Aquifer Pollution Using The DRASTIC Method

The compilation of all the maps and the calculation of the vulnerability index of the seven DRASTIC parameters made it possible to draw up a water vulnerability map that allows the visualization of the main areas at risk of pollution for the shallow and deep water tables.

The distribution of the vulnerability classes according to Figure 5 permits the distinction of five classes according to their pollution risk. The reading of the vulnerability map for the shallow water table (Figure 14a) highlights:

- An area of very high vulnerability occupying 19.95 % of the studied area is located principally near the coastal zone and to the south of the plain, where the spread of the pollutant from the ground surface is facilitated by the high permeability of the sandy formations, a

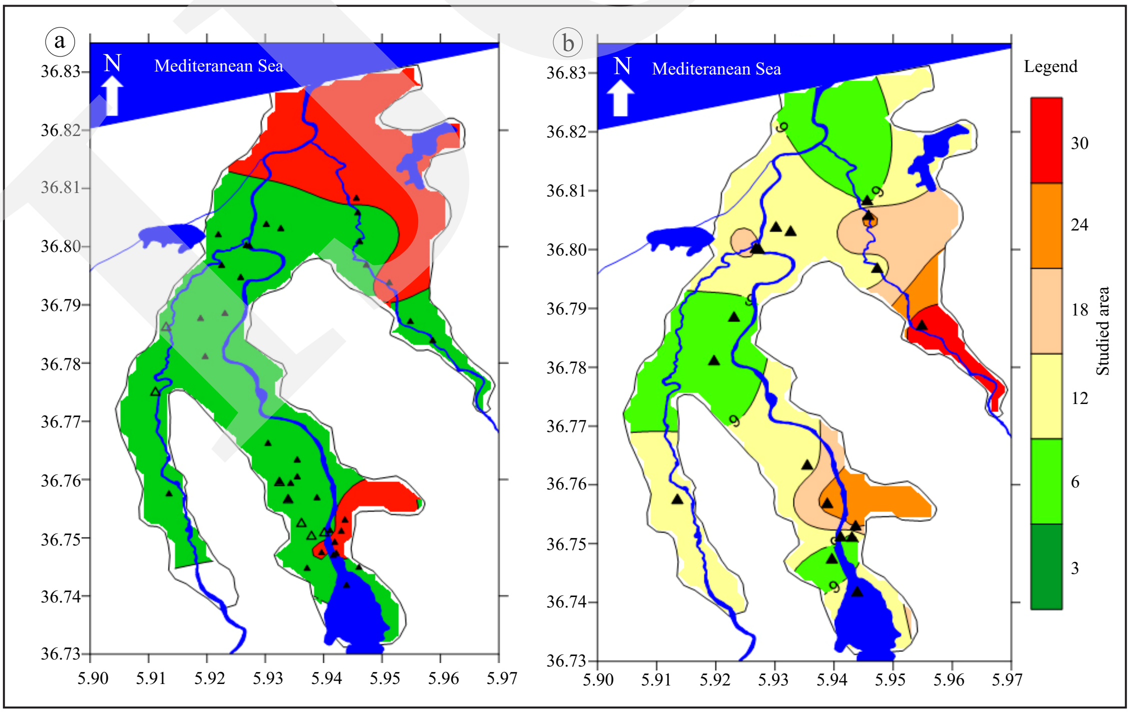

Figure 13. Map of the hydraulic conductivity index (IC) of the Wadi Nil alluvial plain. a) Shallow groundwater, b) Deep groundwater.

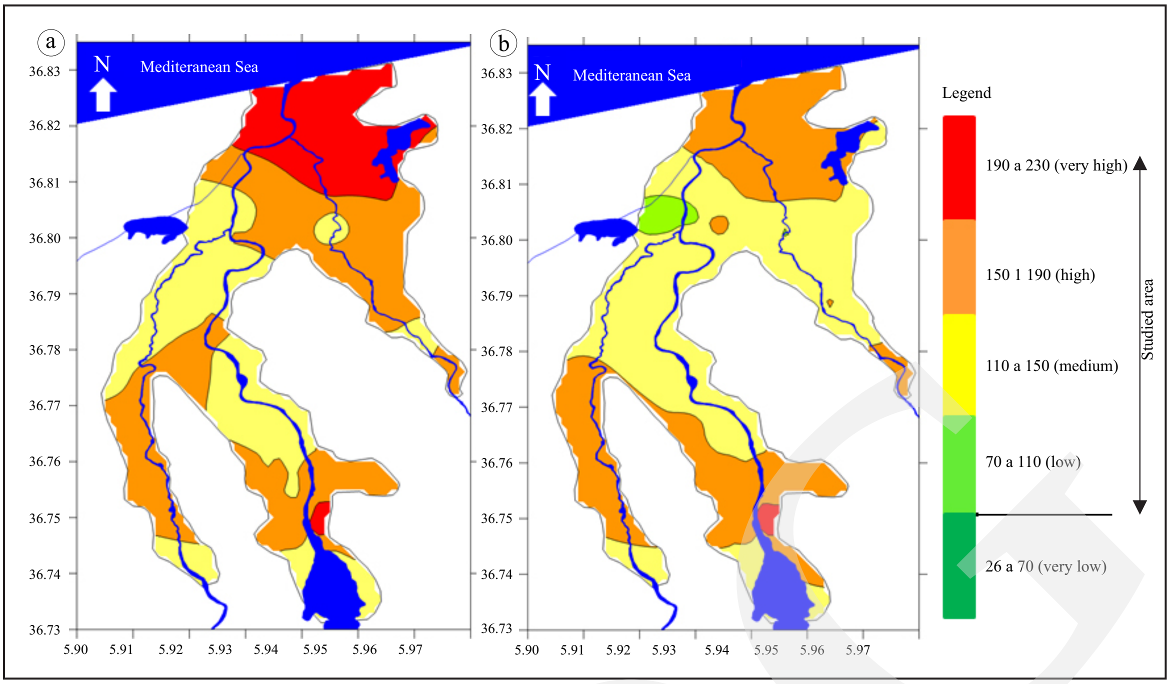

Figure 14. Maps of vulnerability to pollution in the alluvial plain of Wadi Nil. a). Indicates the superficial water table, and b). indicates the deep water table.

shallow saturation zone, flat topography, and terrain favouring infiltration. It is characterized by a very high vulnerability index ranging from 190 to 230, and is coloured red on the vulnerability map.

- A zone of high vulnerability representing 43.39 % of the studied area is located in the centre, east, west, and south of the plain. It is characterized by a high vulnerability index ranging from 150 to 190, and is coloured beige on the vulnerability map.
- A zone of medium vulnerability, representing 36.66 % of the area is situated in the centre and south of the plain, characterized by a fairly high saturated zone with moderate permeability and low slopes with a medium vulnerability index ranging from 110 to 150, and is coloured yellow on the vulnerability map.

With regards to the vulnerability map of the deep water table (Figure 14b), there are several zones of vulnerability:

- An area of very high vulnerability which occupies 0.73 % of the studied area is observed in the south-east of the plain due to the nature of the formations and the shallow water depth. It is distinguished by a very high vulnerability index ranging from 190 to 230, and has been assigned the colour red on the vulnerability map of the Wadi Nil alluvial plain.
- An area of high vulnerability which represents 44.42 % of the studied area is recognied in the north and south of the plain mainly due to the lithological nature of the dune (sand) and alluvial (gravel, sand, and pebble) formations favourable to the transfer of contaminants. It is characterized by both a low slope and high values of hydraulic conductivity, with a high vulnerability index ranging from 150 to 190, and has been assigned the colour beige on the vulnerability map of the Wadi Nil alluvial plain.
- An area of average vulnerability representing 52.68 % of the surface area in the studied area, occupies the centre and extreme south of the plain. It is characterized by average permeabilities and low slopes. It is marked by a medium vulnerability index ranging from 110 to 150, and the colour yellow has been attributed to it on the vulnerability map of the Wadi Nil alluvial plain.

- An area of low vulnerability represented by 2.17 % of the studied area, occupies the northeast near the Redjla swamp and the confluence of the Nil and Boukraa wadis. It is distinguished by a relatively low permeability where the unsaturated zone is significant. It is characterized by a low vulnerability index ranging from 70 to 110, and has been assigned a light green colour on the vulnerability map of the Wadi Nil alluvial plain.

Statistical Analysis of DRASTIC Parameters

The DRASTIC method assesses vulnerability using the weighted sum of seven parameters. Many scientists affirm that the subjectivity of the scoring and weighting system can strongly affect the results of vulnerability indices (Napolitano and Fabbri, 1996). Sensitivity analysis provides useful and valuable information on the influence of the scoring and weighting values assigned to each parameter and helps researchers to judge the importance of the elements accurately (Gogu and Dassargue, 2000).

A statistical summary of the seven parameters used to calculate the DRASTIC index in the Wadi Nil alluvial plain is presented in Table 3. By analyzing the averages of the indices of each criteria in shallow water, it is shown that the greatest risk parameter of contamination to groundwater is water depth, the parameter which has the highest average (47.76). Next is the parameter recharge (34.07), then the impact of the vadose zone (27.58), followed by the aquifer environment (24). The hydraulic conductivity parameter exhibits a moderate risk on the system (average of 11.36). The soil type and topography parameters seem to hold little sway on the vulnerability of a system (their respective averages were: 9.35 and 9.85). The coefficient of variation for the shallow water table shows that the largest contribution to variations in the vulnerability index is due to the hydraulic conductivity parameter (CV= 109.89 %). The parameters soil, vadose zone impact, and topography show the average contributions (CV= 51.01 %, 31.55 %, 13.80 %); recharge and water depth show low contributions (CV= 10.86 %, 5.51 %); and the aquifer showed a net-zero contribution (CV= 0 %) due to a structure considered to be entirely composed of alluvium. By comparing the means with the coefficients of variation, the approach appears relatively robust as the parameters with the strongest influences

Table 3. Summary Statistics of DRASTIC Parameters

Shallow water table									
	Vulnerability parameters							DRASTIC Vulnerability	
	D	R	A	S	T	I	C		
Min	35	20	24	2	1	5	3	120	Medium
Max	50	40	24	18	10	40	30	212	Very high
Mean	47.76	34.07	24	9.85	9.35	27.58	11.36	164.09	High
SD	2.63	3.7	0	5.02	1.29	8.7	12.48	25.72	
CV	5.51 %	10.86 %	0.00 %	51.01 %	13.80 %	31.55 %	109.89 %	15.68 %	

Deep water table									
	Vulnerability parameters							DRASTIC Vulnerability	
	D	R	A	S	T	I	C		
Min	5	20	24	2	1	5	6	97	Low
Max	50	40	24	18	10	40	30	190	High
Mean	31.04	34.07	24	9.85	9.35	27.58	12.51	148.5	Medium
SD	11.62	3.7	0	5.02	1.29	8.7	5.99	16.28	
CV	37.44 %	10.86 %	0.00 %	51.01 %	13.80 %	31.55 %	47.91	10.97 %	

are consistent between the two approaches, with the exception of the impact of the vadose zone.

Analysis of the deep water table averages shows that the greatest risk of groundwater contamination is from the recharge parameter, which has the highest average (34.07). Following this is the water depth (31.04), the impact of the vadose zone (27.58), and the aquifer environment (24). The hydraulic conductivity parameter contributes moderately to vulnerability (average of 12.51); and the soil type and topography parameters has a low impact on vulnerability (the respective averages are: 9.35 and 9.85). The coefficient of variation for the deep water table shows that the greatest contributions to variations in the vulnerability index are soil type and hydraulic conductivity (CV= 51.01 %, 47.91 %). The parameters of vadose zone impact and topography show average contributions (CV= 31.55 %, 13.80 %), and recharge shows a low contribution (CV= 10.86 %). Finally, the aquifer environment shows a net-zero contribution (CV= 0 %) due to its composition being made up of alluvium. As with the shallow water table, the impact of the vadose zone therefore appears to be the most sensitive parameter.

The Map Removal Sensitivity Analysis Test

The DRASTIC method is based on the use of several parameters. Barber *et al*. (1993) suggested that the development of the groundwater vulnerability map can be done without the use of these parameters. On the other hand, Napolitano and Fabbri (1996) criticized the accuracy of the vulnerability index developed with the different weights and scores used in the model. In order to avoid any ambiguity in our results, a study on the sensitivity of the method was carried out using the "Map removal sensitivity analysis" test proposed by Lodwick *et al*. (1990), which allows the sensitivity of the vulnerability map to be determined by removing one or more parameters at a time, with the aim of establishing the significance of the parameters used to establish the DRASTIC model. The statistical results are presented in Tables 4 and 5. Table 4 shows the variation in the vulnerability index for shallow and deep water tables as a result of removing a single DRASTIC parameter. For the shallow water table, on the one hand, the soil type, topography, and hydraulic conductivity parameters have the least effect on the variation of the final vulnerability

Table 4. Statistics of The Map Removal Sensitivity Analysis Test

	Shallow water table				Deep water table		
	Min (%)	**Max (%)**	**Mean (%)**		**Min (%)**	**Max (%)**	**Mean (%)**
D	21.55	40.44	29.75	**D**	4.55	37.02	20.71
R	16.01	26.88	20.99	**R**	16.37	32.90	23.08
A	11.30	20.00	14.96	**A**	12.59	24.68	16.38
S	1.16	12.09	5.81	**S**	1.19	13.16	6.53
T	0.48	8.33	5.83	**T**	0.60	10.28	6.39
I	3.32	24.60	16.53	**I**	3.09	28.45	18.36
C	0.51	18.05	6.13	**C**	3.16	20.63	8.55

Table 5. Statistics of The Map Removal Sensitivity Analysis Test

	Superficial water table		
	Min (%)	**Max (%)**	**Mean (%)**
D, R, I, A, C and T	1.16	12.09	5.81
D, R, I, A, and C	6.14	18.66	11.64
D, R, I and A	8.76	29.82	17.77
D, R and I	24.32	43.47	32.73
D and R	38.14	59.26	49.26
D	59.56	78.45	70.25

index with low averages (5.81 %, 5.83 %, 6.13 %). On the other hand, the parameters of water depth, recharge, impact of the vadose zone, and aquifer environment are responsible for the large variation in the vulnerability index with higher respective averages (29.75 %, 20.99 %, 16.53 %, 14.96 %). Vulnerability seems to be very sensitive to the suppression of the water depth parameter, knowing that this parameter is theoretically considered the highest, with a weight of 5.

For the deep water, on the one hand, the topography, soil type, and hydraulic conductivity parameters are those that affect the least the variation of the final vulnerability index with low averages (6.39 %, 6.53 %, and 8.55 %, respectively). On the other hand, the recharge, water depth, impact of the vadose zone, and aquifer environment parameters are responsible for the large variation in the vulnerability index with respective averages that are higher (23.08 %, 20.71 %, 18.36 %, 16.38 %). Vulnerability seems to be very sensitive to the removal of the recharge parameter, to which a theoretical weight of 4 is attributed.

Conclusions

The vulnerability of the Wadi Nil alluvial groundwater was assessed using the DRASTIC method. Through this work, the interest of using the DRASTIC method in combination with Geographic Information System (GIS) techniques to delimit the areas presenting a high pollution risk was demonstrated.

The thematic maps elaborated can be used as a support for the analysis of risks to groundwater pollution, by cross-referencing these vulnerability maps with hazard maps (diffuse contamination such as areas of intensive agriculture and occasional contamination such as wastewater discharge, urban waste storage, or sensitive industrial activities).

Seven DRASTIC parameters (Depth of the water table, Net Recharge, lithology of the saturated zone, Soil type, Topographic slope, lithology of the unsaturated zone, and hydraulic Conductivity) were used to calculate the vulnerability indices to pollution of the Wadi Nil alluvial plain.

The calculated DRASTIC indices vary between 26 and 230. This made it is possible to classify the vulnerability into five classes (very low, low, medium, high, very high). The vulnerability of these classes can change due to the combined effects of human activities and rainfall regime.

The mapping of the vulnerability of the Wadi Nil alluvial plain using the DRASTIC method for the shallow water table showed areas with the very high vulnerability occupying 19.95 % of the area, high vulnerability 43.39 %, and average vulnerability 36.66 %. For the deep water table, very high vulnerability zones occupy 0.73 % of the area, high vulnerability 44.42 %, medium vulnerability 52.68 %, and low vulnerability 2.17 %. This means that the shallow and the deep water tables are threatened by the infiltration of pollutants from the surface. It can also be noted that areas of very high and high vulnerability coincide with areas of intense agricultural activity and urban and peri-urban areas, which represent a major risk to the quality of groundwater.

The statistical analyses and sensitivity analysis highlighted the importance of all DRASTIC parameters in the elaboration of the final model of the studied area, with a predominant influence of the water depth, recharge, and impact of the vadose zone parameters for both the shallow and deep water tables. The sensitivity analysis showed that the approach is relatively robust even if the parameter impact of the vadose zone seems sensitive and associated with uncertainties.

The DRASTIC vulnerability map gives a fairly precise idea of the different zones of vulnerability in the region. Therefore, it is recommended that decision makers use this vulnerability map to assess and understand the mechanisms of contamination and groundwater recharge. In addition, it would be interesting to carry out more detailed studies on the local conditions of this region. This would make it possible to improve land use planning and management for the sustainable protection of water resources, and to protect the water table from all sources of pollution.

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