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# Groundwater vulnerability assessment using GIS modeling for north-east area of Tadla plain (Morocco)

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**ABSTRACT**

The groundwater resources in Tadla region are the most unique principal source of water for drinking, agriculture, irrigations, and agro-industrial activities. Further, they are more vulnerable to pollution, especially aquifers those situated in arid and semi-arid regions, as the north-east area of the Tadla plain. The growing up of demography, economics, intensive agriculture and agro-industrial activities affect directly the basin by more susceptible contaminations. This negative impacts on the hydrogeological system intensifying the risk of the aquifer to pollution. For these reasons, the aim of this study is to define the degree of intrinsic vulnerability of this groundwater to any type of contaminants introduced from the soil surface. The importance of this research revolved around evaluating the vulnerability of groundwater aquifers using DRASTIC method coupled with Geographic Information System, the method is founded on diverse parameters: recharge of the tablecloth, the nature of the soil, depth of the water table, topography and the impact of the unsaturated area. The analysis of the intrinsic vulnerability maps allowed for determining three classes ranging from low to high vulnerability. The southeastern part of the study area shows the highest vulnerability class, and the north part show a minor vulnerability class, this area is localized in a desert and uninhabited sectors of the study area, which are less populated, where human impact on the groundwater is minimal. The highest class indicating that it is the most vulnerable to contamination due to the hydrogeological intrinsic factors. The advantage of this approach make it easily possible to investigate and control vulnerability of the area.

*Keywords:* Vulnerability; Pollution; DRASTIC; Geographic Information System; Tadla plain,

## 1. Introduction

Pollution is increasingly threatening groundwater supplies, water quality degradation is occurring as a result of increased human activity. Agricultural, urban, and industrial activity have all contributed to the potential contamination of water resources in recent decades. Prevention against aquifer pollution is an important step that scientists are making more and more effort to take, particularly by studying the vulnerability of groundwater. Vulnerability maps may be used to detect spaces where groundwater pollution is a possibility. This allows us to avoid places where anthropogenic

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action (farming, garbage, industry) poses a contamination risk, as well as the primary upkeep of biological systems. Vulnerability is the common inability to secure groundwater against the dangers of contamination, as per neighborhood hydrogeological conditions. As such, the term vulnerability is used to address the regular highlights that decide the affectability of groundwater to contamination [1,2]. As per the writing, vulnerability might be either explicit or inborn. The initial term considers the properties of a toxin or a gathering of impurities. The subsequent term comprises of the geographical, hydrological, and hydrogeological qualities of the examination zone yet is autonomous from pollutants. This next term which develops various techniques formed [1,3–5].

The studies made on the groundwater of Tadla plain, placed in a plain mainly exploited for agriculture, with a truly expanding utilization of chemical fertilizers.

The Tadla plain covers an area of 3,600 km$^2$ and extends approximately to the north of the high Atlas Mountains [6]. It lies between 6°42′21″W and 6°16′03″W longitude and 32°28′49″N 32°31′10″N latitude (Fig. 1), and bounded to the north by the plateau of phosphates which gradually ascends unmarked a transitional net to the east of the narrowed plain along the Oum-Erbia climatologic data reveal a semi-arid climate to contrasted seasons for the region [7,8]. Rainfall is relatively important in the east and in zones neighboring the Atlas Mountains such as Dcher El Oued (507 mm/y) and Qasbat Tadla (368 mm/y). From east to west, annual precipitation decreases (315 mm in Khouribga) and southwest (211 mm in Oulad Sidi Driss) [7,8].

The average altitude varies from 350 to 500 m with the lowest point in Sidi Driss (hydrological station on the Oum-Errbia) and the highest on main road 24 near Tighboula (about 750 m) [9].

The hydro-agricultural plan covers an area of 1,200 km$^2$ from Tadla plain, whose soil potential and horizontal topography are two favorable elements for a large extension of different crops [10]. Agriculture contributes to the pollution of the slicks because of the sometimes irrational utilization of composts and pesticides that farmers add in order to increase the productivity of the plot. The amount of nitrogen leached into the water table or trickled into streams is estimated at about 10%; about 3,500 tons of nitrates from fertilizers reach the Tadla slick by leaching [11]. In addition, pesticide pollution has been expected at 2.2 ton/y [12,13].

The Tadla depression is geologically linked to the southern Moroccan Meseta, namely the “Bahira-Tadla” synclinal zone (Fig. 2). It presents itself as a synclinal bowl filled with a sedimentary series whose age extends from the Permo-Triassic Quaternary. Throughout the basin, quaternary overlays completely obscure the underlying lands [14].

As a result, the only geological data accessible is from a few deep boreholes. These drillings have shown the existence of the geological layers depicted in the diagram below. The aquifer’s Tadla plain complex covers a large portion (10,000 km$^2$) of the middle Oum-Erabia river basin [15]. It is described as a succession of hydrogeological units of varying hydraulic importance. This multilayered aquifer is made up of four main aquifers that are connected hydraulically. These are from the bottom up: the carbonate aquifer of the Turonian, locally the Cenomano-Turonian; the carbonate aquifer of the Senonian; the Eocene calcareous-sand aquifer and the Mio-Plio-Quaternary alluvial aquifers [16].

These aquifers have a thickness and a roof that generally increases from east to west. The Mio-Plio-Quaternary aquifer is represented by a very heterogeneous lake river complex, including an alternation of marno-limestone, lake limestone and conglomerates. This well-individualized hydrogeological entity consists of two slicks located on either side of the Oum-Erabia: Beni Amir slick to the north and the Beni Moussa slick to the south [17].

The most famous vulnerability models were applied previously for the studied area; while it is very important to

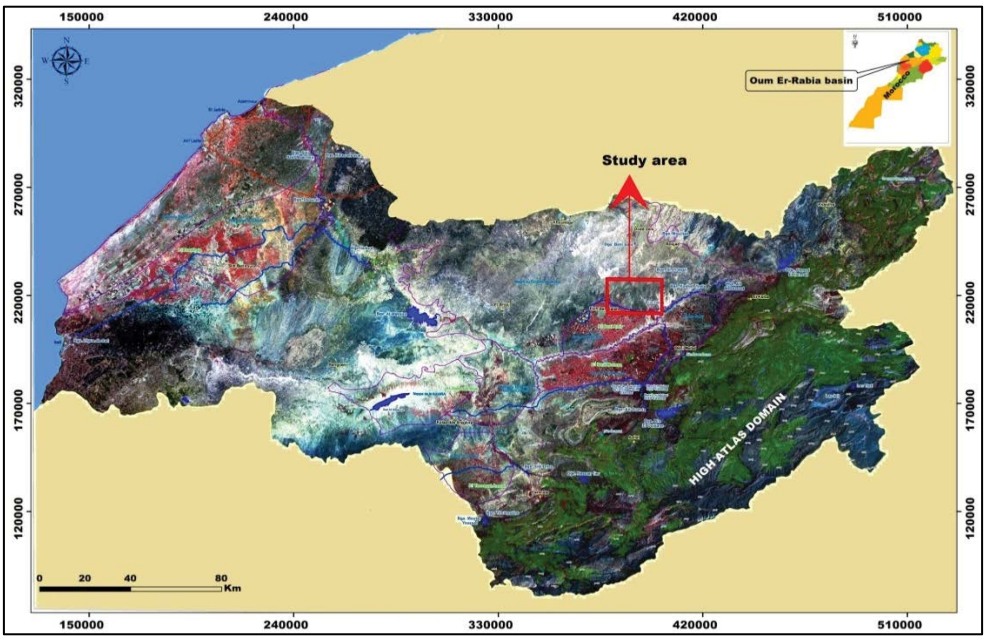


Fig. 1. Location map of the study area.

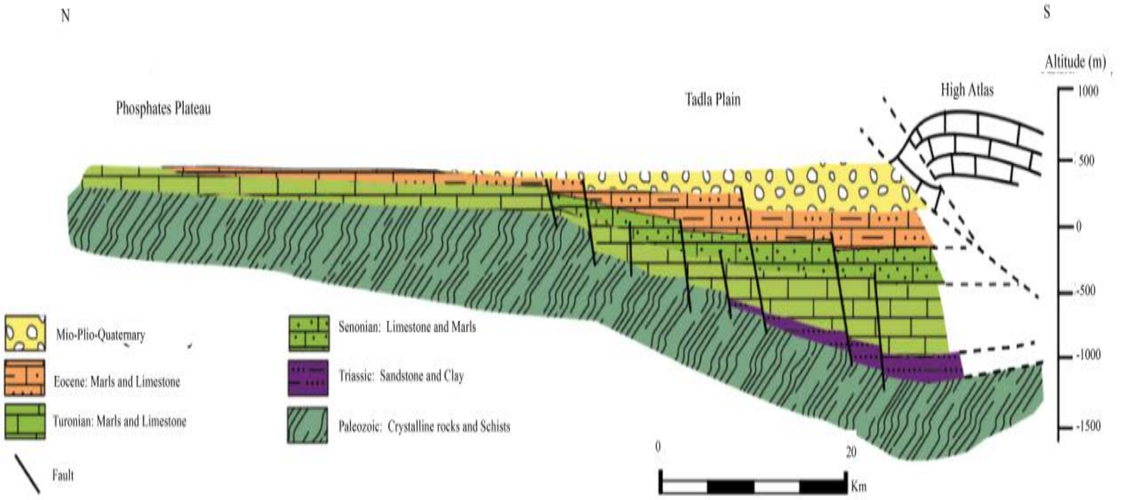


Fig. 2. Geological cut from north to south of the Tadla and Atlas plain phosphate plateau [15].

confirm the computed vulnerability, model is reflecting the real vulnerability system for the study area: The DRASTIC technique just considers the hydrogeological factors affecting weakness. These actual properties that game a role in the movement and reducing of contaminants in the soil complex ventilated region aquifer. Seven parameters are thought of the profundity of the water, the annual effective aquifer recharge, spring lithology, soil type, topography, effect of the vadose zone and pressure driven conductivity the aquifer 315 m). Consequently, this work was completed to check the validity of the strategy for standard exceptional weakness [1]. It takes into the intrinsic characters of the aquifer by revealing his predisposition or vulnerability to contamination-related activity from the soil surface. So, the main objective of the current study is to assess groundwater vulnerability to pollution in Tadla aquifer using the DRASTIC model. This model is based on the seven data layers that provide the input to the modeling. It corresponds to the initials of seven layers, that is, depth of water, net recharge, aquifer media, soil media, topography, impact of vadose zone and hydraulic conductivity.

## 2. Materials and methods

In order to determine the aquifer's susceptibility to pollution contamination in the Tadla plain, a DRASTIC model was used. Information about the model's layers was given through a Geographic Information System (GIS). ArcGIS 10 software was used to construct an interactive geodatabase, compile geospatial data, compute DRASTIC indices, produce vulnerability maps, and perform sensitivity analysis.

### *2.1. Vulnerability assessment*

#### *2.1.1. DRASTIC method*

One of the most widely used groundwater vulnerability assessment methods is DRASTIC, established in the US Environmental Protection Agency (EPA) as a technique for evaluating groundwater pollution potential [1].

The initials of the seven hydrogeological parameters are abbreviated as DRASTIC: depth to water, aquifer media, net recharge, soil media, topography, impact of vadose zone media, and hydraulic conductivity of the aquifer. These parameters are the most essential mapable factors which control the groundwater contamination potential. The DRASTIC technique results in a standardized approach that can be used to screen regions for groundwater safety monitoring and cleanup efforts. DRASTIC models may help delimit areas where pesticides, municipal and industrial contaminants can end up posing a greater risk to groundwater. The data on the different parameters used for the estimation of the contamination risk are mapped using a Geographic Information System (GIS). Subsection maps showing local conditions have been made for each parameter. A notation from 1 to 10 is attributed to each fragment of a given map according to the DRASTIC charter (Table 1). A value of 1–5 is given to each factor according to its importance (Table 2). The DRASTIC vulnerability index represented vulnerability index (ID) [Eq. (1)] was developed to define the level of vulnerability of each hydrogeological unit. The ID was calculated by summing the products of the weight measured from the corresponding parameters according to Eq. (1):

$$\text{ID} = (Dc \times Dp) + (Rc \times Rp) + (Ac \times Ap) + (Sc \times Sp) + (Tc \times Tp) + (Ic \times Ip) + (Cc \times Cp) \tag{1}$$

where *D*, *R*, *A*, *S*, *T*, *I* and *C* are the seven parameters of the DRASTIC process, Table 1. The parameter's weight is denoted by "*p*" and the corresponding rating is denoted by "*c*", the values of the weight parameters of the DRASTIC process used are those defined by the study of Aller et al. [1]. These values are shown in Table 2. As the values of the DRASTIC index used, they are provided by the study of Bézèlgues and Mardhel [18], and represent the extent of the hydrogeological aquifer vulnerability. This index spans the whole range from 23 to 230 [19]. These values represent the range of the hydrogeological aquifer vulnerability and are within the range of theoretical values according to the classification by the study of Engel et al. [19]. As mentioned in (Table 1), the other classification will set limits intervals considered indices and match intervals of these indices vulnerability.

The mapping approach was carried out using Geographic Information Systems (GIS) utilizing ArcGIS software and allows to compile spatial data, calculate indices from the geographical distribution of weighted scores assigned to the seven parameters, and to make the vulnerability map that represents the variety in vulnerability indices. Classifying these indices according to DRASTIC classes allows the relative vulnerability of each sector studied to be spatialized. Fig. 3 represents the different phases of the development of the vulnerability map.

## 3. Results and discussions

The resulting maps permit us to visualize the relative degree of vulnerability of a region of the study area. The potential for contamination increases in the same direction as the index. The DRASTIC vulnerability index represents an evolution of the level of risk of contamination of an aquifer formation. This risk increases with the value of the index. This can take a maximum value of 226 and a minimum value of 23. For each of the DRASTIC process's seven parameters, a thematic map is created. On each of these maps, the areas characterized by a partial vulnerability index of the corresponding parameter are delineated.

Table 1
Vulnerability classification in standard DRASTIC [19]

| Index intervals | DRASTIC index | Degree of vulnerability |
|---|---|---|
| 23–79 | 8 | Very low |
| 80–99 | 7 | Low |
| 100–119 | 6 | |
| 120–139 | 5 | Average |
| 140–159 | 4 | |
| 160–179 | 3 | High |
| 188–199 | 2 | |
| 200–230 | 1 | Very high |

### 3.1. Depth to water (D)

Depth to water level is one of the principal factors in any vulnerability model since it determines the thickness of material through which infiltrating water should pass before reaching the aquifer-saturated zone [5,20].

During this investigation a companion of piezometric measurements was carried from the surveys of 40 wells. These measurements were used in mapping and assessing the vulnerability to pollution of the aquifer relative to the depth of the slick (Fig. 4). These point data were contoured by interpolating and divided into three categories, that is, <1, 1–3, and >3 m (Fig. 4). Thereafter it was converted into grid to make it raster data for GIS operation. In general, the vulnerable area is located in the northern part with red color in the map, but the southern parts of Tadla plain reveal low vulnerability to contamination with yellow color.

### 3.2. Recharge (R)

The recharge is the amount of water from precipitation available to migrate down to the groundwater. Recharge water is, therefore, a significant vehicle for percolating and transporting contaminants within the vadose zone to the saturated zone. It carries the solid and liquid contaminants reached from surface, also from irrigation water that contributes more to the groundwater pollution because of fertilizer and pesticides used in agricultural activities.

The calculation of the infiltrated fraction is done by several methods depending on the nature of the aquifer and the type of climate that characterizes the region. In the region, groundwater is recharged by direct infiltration of meteoric

Table 2
Weight of parameters in the standard DRASTIC method [1]

| Symbol | Parameter | Properties | Weight |
|---|---|---|---|
| *D* | Depth of the tablecloth | Higher the depth, the longer it takes for the contaminant to reach the piezometric surface. | 5 |
| *R* | Net recharge | Main vehicle for transporting the contaminant, the greater the recharge, the greater the risk of contamination. | 4 |
| *A* | Aquifer lithology | Characterized by the granulometry of saturated terrain. It is involved in trapping pollutant that can evade the soil's ability to absorb it. The finer the granulometry, the greater the trapping of the pollutant. | 3 |
| *S* | Ground | Richer the soil is in clay, the greater the absorption of heavy metals and the greater the protection of groundwater. | 2 |
| *T* | Topography | Precipitous the slope of the land, the greater the runoff and therefore the lower groundwater pollution. | 1 |
| *I* | Unsaturated area | Its impact is determined from the texture of the land that makes it up. The percolation of the pollutant to the piezometric surface is all the greater as this texture is favorable (gravel, coarse sands). | 5 |
| *C* | Permeability | The larger the parameter, the faster the transfer of the pollutant. | 3 |

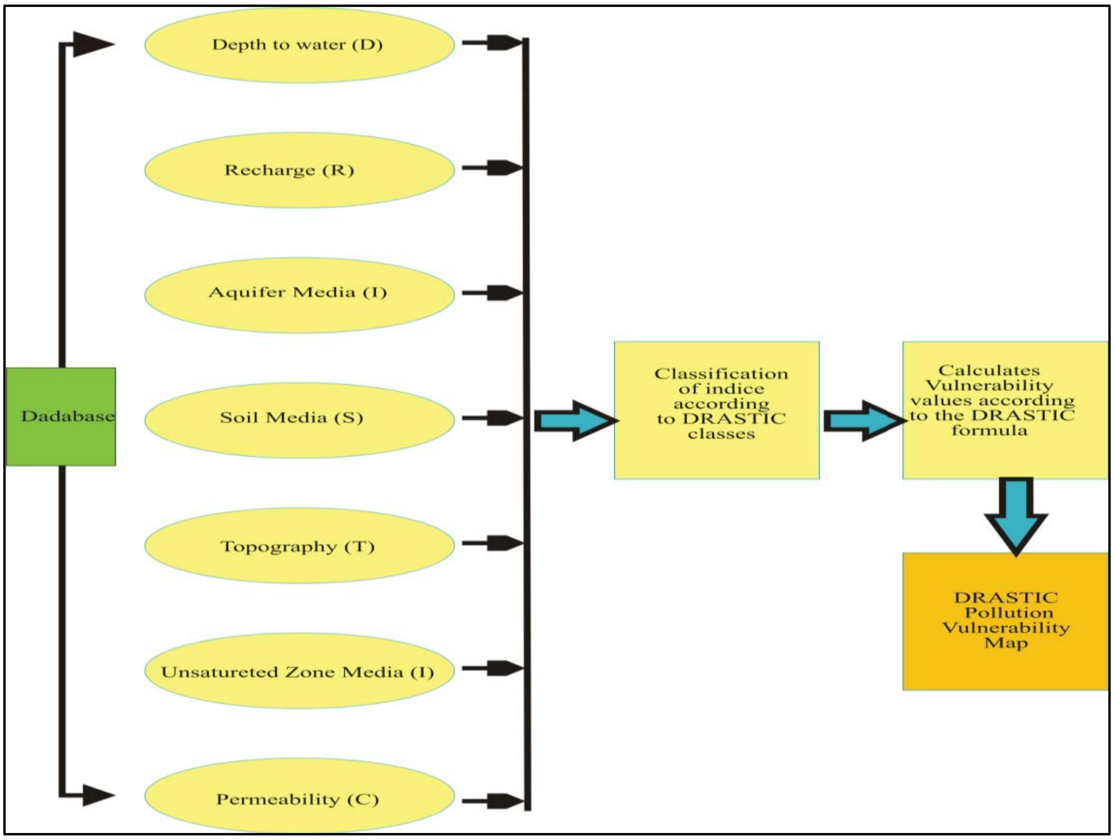


Fig. 3. Flow chart showing analytical hierarchical process based DRASTIC modelling for groundwater vulnerability assessment.

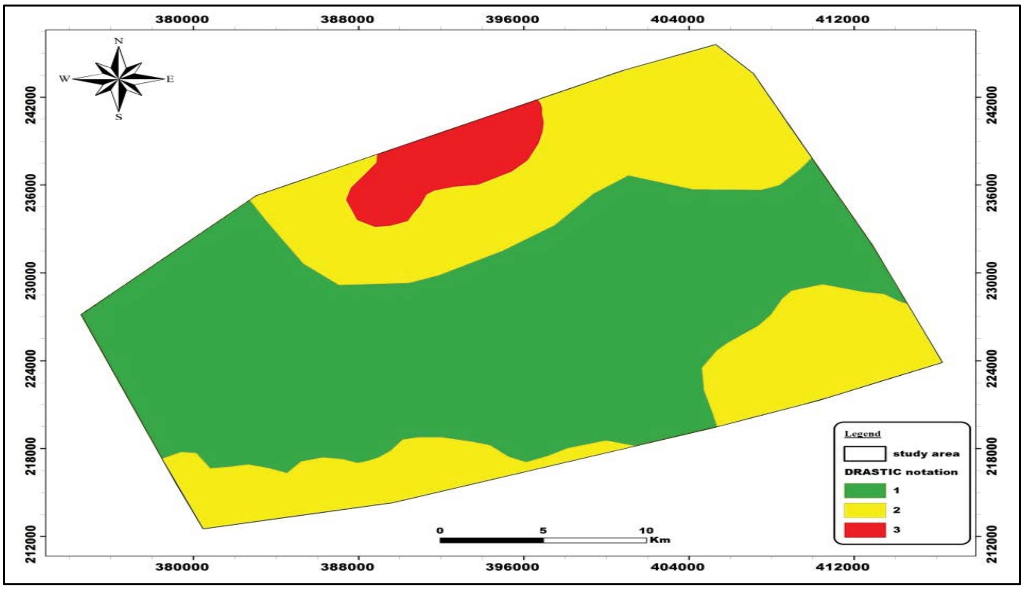


Fig. 4. Spatial distribution of depth to water level of the study area.

water. All data-wells between 1985–2019 and the geological map of the study area are used from ABHOER database to calculate the net recharge rate of the aquifers (Fig. 5). Potential net recharge is considered to varies from <5 to >9 in (Fig. 5) [21]. The net recharge estimate formula is listed below:

$$R_{\text{net}} = \left(P - \text{ETR}\right)W = \left(E + 1\right)W \quad (2)$$

where the followed parameters explain $R_{\text{net}}$: net recharge; $P$: precipitation in mm; ETR: actual evapotranspiration in mm; *W*: infiltration coefficient in %; *E*: runoff in mm; and *I*: infiltration in mm.

### 3.3. Aquifer media (A)

Aquifer media refers to a rock in the ground that serves as water storage [22]. It indicates materials property that controls pollutant attenuation processes based on the permeability of each layer [23]. The attenuation characteristic of the aquifer material is reflected by the mobility of the contaminants through aquifer media.

The lithology of aquifers is characterized by deposits of the river, and gravies in the southern part (Fig. 6), clays and clay sand in the center and in the north, limestone and sand in the northeastern part of the study region. In general, larger the grain-size and the more fractures or openings within the aquifers, the higher the permeability and lower the attenuation capacity; consequently the greater the pollution potential [3]. So the coarse (saturated or unsaturated) media was assigned a high rating value compared to the fine media.

### 3.4. Soil media (S)

The properties of soils control the measure of water that may infiltrate the ground surface and arrive at the groundwater [24]. Permeable soils, such as sandor gravel, permit more water to infiltrate to the water table, making groundwater more vulnerable, while less permeable soils such as clays, allow less infiltration [25] with less groundwater vulnerability. Infiltration is the important factor in transporting agricultural pollutants from the surface, through the soil profile, to the groundwater.

The characteristics of soil influence the amount of recharge infiltrating the ground surface, the amount of potential dispersion, the purifying process of contaminants, etc. Soil cover characteristics influence the surface and downward movement of contaminants. The presence of fine grain size materials, such as clay, and the percentage of organic matter within the soil cover can decrease intrinsic permeability, and retard or prevent contaminant migration via physico-chemical processes, that is, absorption, ionic exchange, oxidation, and biodegradation.

The final soil map was obtained by merging the data layers and weightages and ratings were assigned (Fig. 7).

### 3.5. Topography (T)

The slope of a region is referred to as topography. Areas with low slope tend to retain water for longer period of time. Areas with steep slopes, having large amounts of runoff and smaller amounts of infiltration are less vulnerable to GW contamination. It determines whether a pollutant will be transported by runoff or will stay on the ground and penetrate into the surface [1], the gentler the slope (slope of

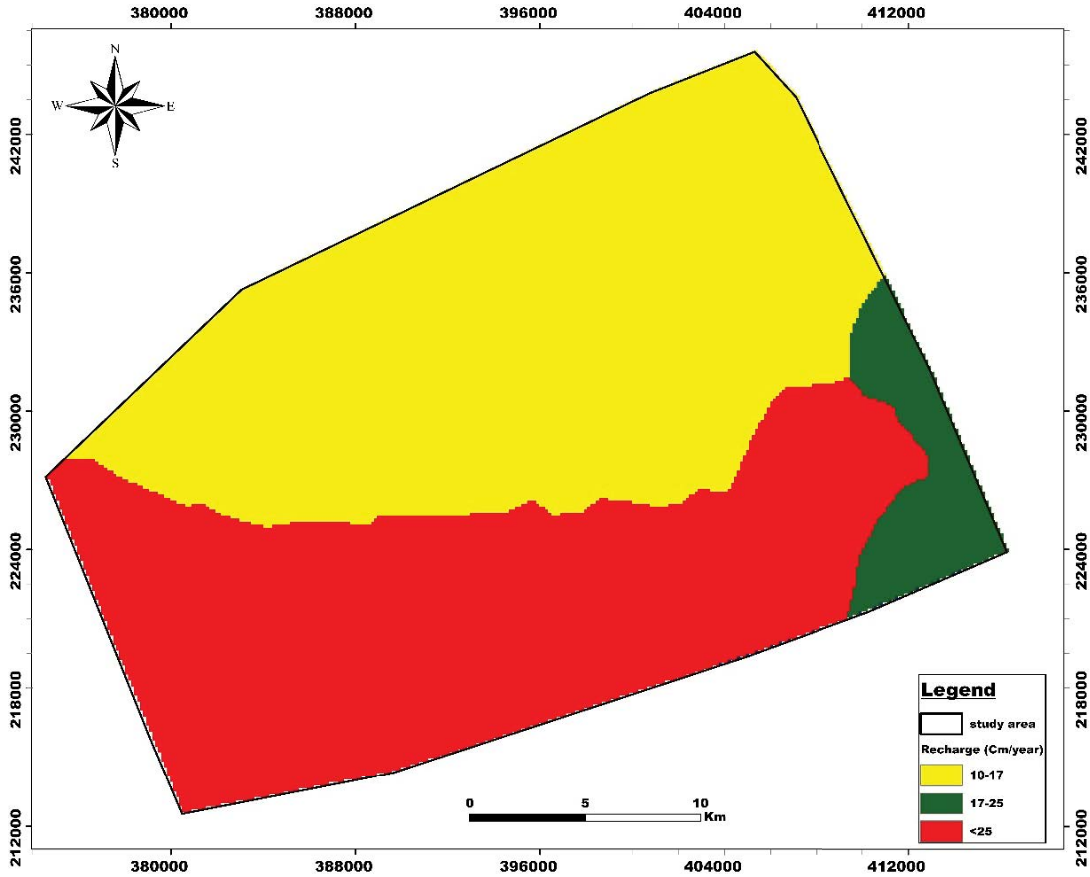


Fig. 5. Spatial distribution of net recharge index of the study area.

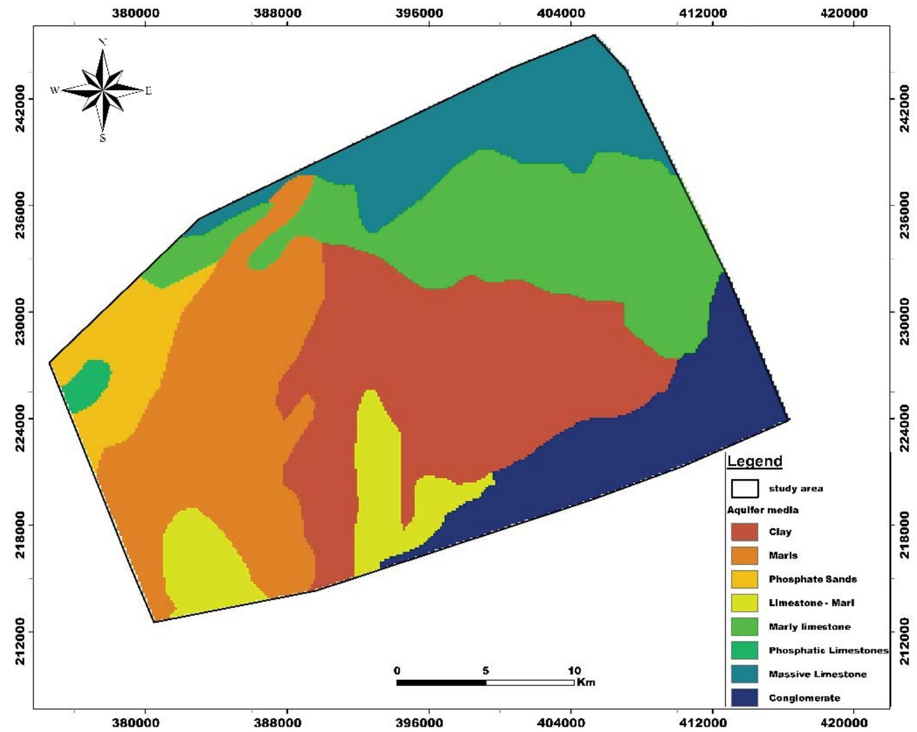


Fig. 6. Spatial distribution of aquifer media of the study area.

0%–2%) the higher the water and/or pollutant retention capacity [1]. There after slope was extracted from the ABHOER survey and it was divided into five classes. Topography will give an indication on whether a pollutant will run off or remain on the surface long enough to infiltrate into the bottom. The numerical terrain model was used to compute the slope at all points of the study area. Slope variation in the study area is very small, that is, <1, 1–10, and >10 m. The map developed after classification of each pixel, according to the rating systems, shows that almost the entire region is characterized by a very low slope, less than 2° (Fig. 8).

### 3.6. Vadose zone media (I)

The vadose zone is the unsaturated extension of the saturated zone of the aquifer. Its materials, similar the soils above, control the measure of water, and accordingly contaminants, which penetrate to the saturated zone [24]. An elevated permeability such as sandstone, will authorize more water to infiltrate through than a lower permeability such as clay-rich layer [25]. Aquifers with higher permeability are more susceptible to pollution (Fig. 9).

The plan is similar to that for the soil media [1], where clay-rich surfaces are impermeable to pollutants and thus collect a lower rating, while gravels and sands are rather permeable and allow more pollutants to reach the groundwater system, and thus receive a higher rating. The effect of the vadose zone is ranked on 1–10 standard scale, with 10 being the most permeable.

### 3.7. Hydraulic conductivity (C)

The establishment of the hydraulic conductivity map estimated the aquifer permeability. The transmissivity determined by test pumping undertaken by the ABHOER [26]. Was divided by the thickness of saturated zone based on drill holes data [27]. High values of hydraulic conductivity of the water table aquifer exceed $10^{-3}$–$10^{-1}$ m/s, indicating important permeability in the southern part and the north-western part of the study area (Fig. 10). They are less than $10^{-9}$–$10^{-7}$ m/s at the center and in the northeast of the studied area.

### 3.8. Vulnerability map

The final vulnerability map was obtained by running the model in ArcGIS environment by using the seven hydro-geological data layers.

The overlay of the seven weighted maps allows the MAP of the DRASTIC index to be obtained on the basis of a linear combination between the different go-their data for each polygon in the attribute table (Fig. 11).

The analysis of the vulnerability map, determined by using the DRASTIC method allowed us to distinguish three classes of different levels of vulnerability, between 23 and 179.

These classes are mainly divided as follows:

- The first high-risk area and extreme vulnerability lies mainly in the municipalities mainly in the southeast, and occupying 3.6% of the total study area. These areas are characterized by all parameters are involved in the increase in the degree of vulnerability: the depth of the slick which varies between 12 and 25 m, the recharge of the tablecloth that exceeds 25 cm/y and the nature of the soil which is characterized by the presence of alluvial texture and the silt that facilitates infiltration.

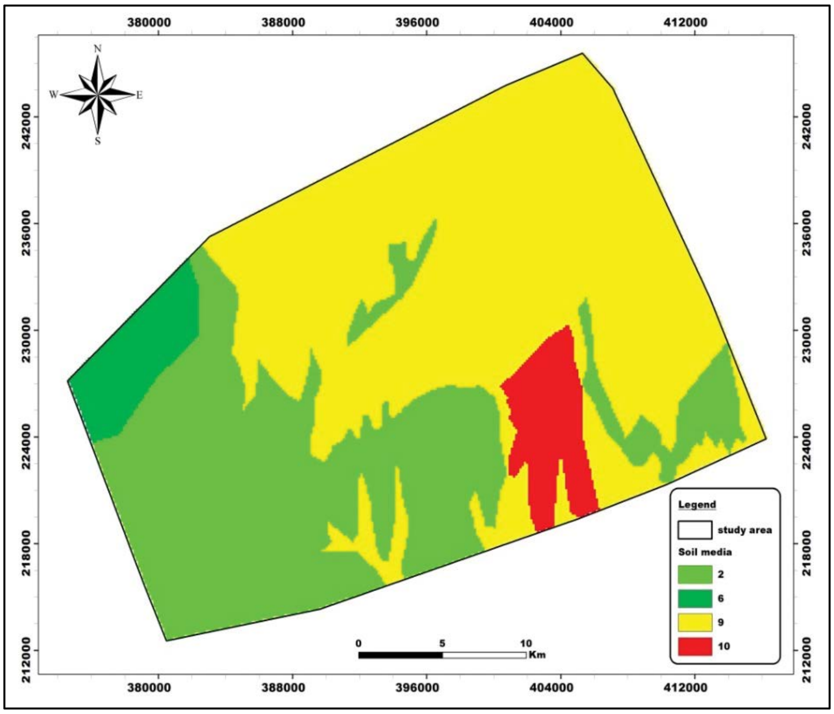


Fig. 7. Spatial distribution of soil texture of the study area.

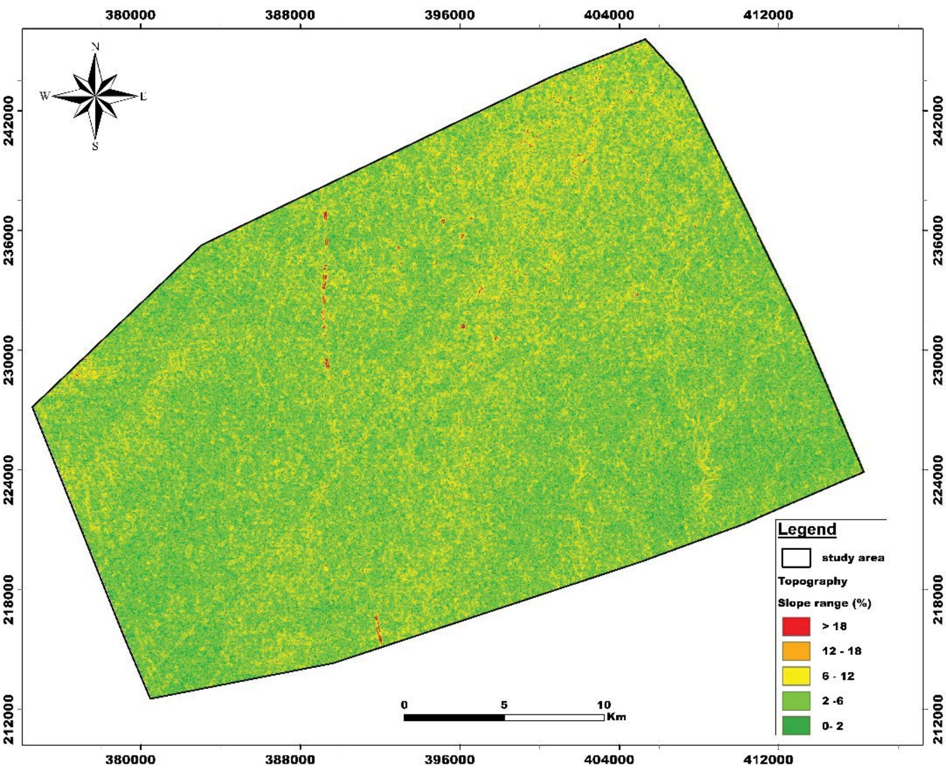


Fig. 8. Slope slick vulnerability map (T).

- The second area includes medium risk vulnerability represented in a large area of the Tadla plain or 38.7% of the total area, they meet in the entire southern part (irrigated area and areas near the Oum-Errabia) and also in the northwestern part of the study area. Generally the topographic slope is low with the presence in some places of large basins favoring the infiltration of water. The depth of the piezometric level is a direct function of

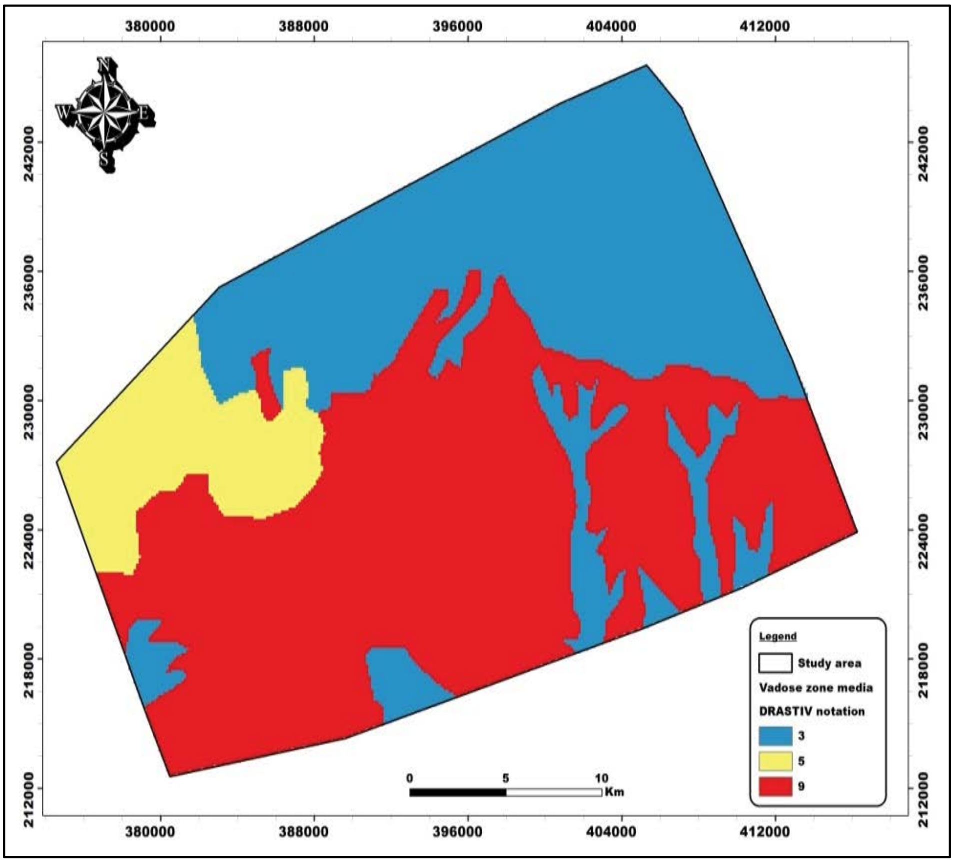


Fig. 9. Spatial distribution of the water table relating to the unsaturated zone (I).

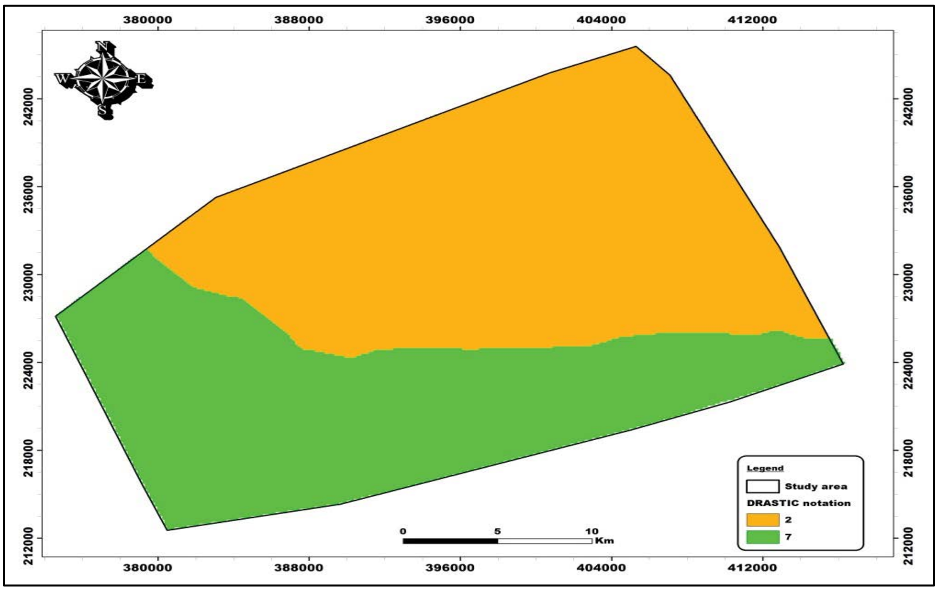


Fig. 10. Spatial distribution of permeability of the study area.

the recharge rate generated by rainwater infiltration.

- The third area of low and very low risk of vulnerability: occupy the largest area, 57.69% of the total area; they meet throughout the northern zone. The various parameters acting on vulnerability to groundwater pollution have intermediate values. The recharge rate is relatively low (non-irrigated area and rainfall generally less than 350 mm), and the low permeability that is lower at $10^{-5}$, these parameters are responsible for this degree of vulnerability.

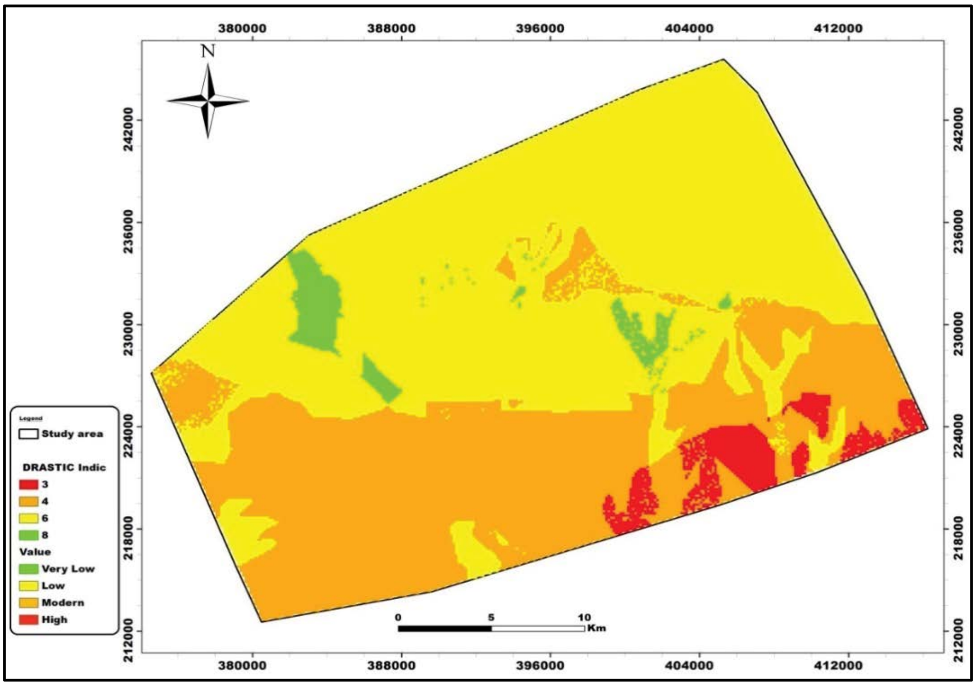


Fig. 11. Groundwater vulnerability map of the study area.

The DRASTIC map produced can be applied to any pollutant which interacts with water at the surface but it does not give a clear picture of the pollution potential of individual chemical constituents as to how much they contribute to the pollution of GW. This is one of the important limitations of this study.

## 4. Conclusion

The GIS-founded DRASTIC model has been utilized to assess the potential groundwater vulnerability in the Tadla plain. The seven DRASTIC parameters have been developed and categorized to calculate vulnerability indices. This was accomplished using the DRASTIC model. The output map was obtained to determine the vulnerability of groundwater pollution.

The spatial distribution of levels of vulnerability to pollution in the slick studied is generally very low to very high, with indices ranging from 23 to 179. They are three classes of vulnerability: very low to low (23–119) and medium (120–160) and more vulnerable (160–170). Areas with very low vulnerabilities occupy almost half of the study area, while the highest indices are located mainly in the southeastern part and occupy 3.6% of the total area studied.

This study produced a very valuable tool for those who are in management position because it gives a very comprehensive indication of vulnerability to groundwater contamination. The high vulnerability of groundwater contamination makes it absolutely necessary to local authorities for managing groundwater resources, monitoring this problem closely and to act accordingly. Infiltration of storm water runoff with respect to groundwater protection showed that the risk of groundwater pollution can only be minimized by using infiltration systems with a passage through the top soil and planning, construction, and operation of infiltration systems. High vulnerable water zones are usually difficult to monitor, as it requires the drilling of many monitoring wells, which is very expensive. The vulnerability map produced in this study gives a decision maker a very comprehensive idea of areas that need to be closely monitored, as well as those areas which are less likely to become contaminated and require less intensive monitoring. The mapping technique used for this analysis is a qualitative method of describing the occurrence and distribution of groundwater pollution.

## Abbreviations

| | | |
|---|---|---|
| GIS | — | Geographic Information System |
| GW | — | Groundwater |
| EPA | — | Environmental Protection Agency |
| ID | — | Vulnerability index |
| DRASTIC | — | D—depth to groundwater, R—recharge rate, A—aquifer, S—soil, T—topography, I—vadose zone’s impact, and C—aquifer’s hydraulic conductivity |
| ETR | — | Actual evapotranspiration |
| ABHOER | — | Oum Errbia Hydraulic Basin Agency |


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