Parametric method used for mapping the groundwater vulnerability to contamination

C Buta¹, C Maftei¹,²,³, G Mihai¹ and M Stânescu¹

¹Ovidius University of Constanta, Bd. Unirii 22 B, Constanta, Romania
²Transilvania University of Brasov, Str. Turnului 5, Brasov, Romania

E-mail: buta.constantin@univ-ovidius.ro; cemaftei@gmail.com

Abstract. Groundwater is a natural resource indispensable for life and for most economic activities. Due to its presentation in time and space, groundwater becomes vulnerable to hazardous phenomena of different origin, natural or anthropogenic, that can produce disturbances in some water systems or default situations. Parametric models can be used to model the groundwater vulnerability and with the help of Geographical Information System (GIS) we can make the results of a complicated parametric model more clearly through visual representation. To achieve the above objective, the empirical model known as “DRASTIC” developed in USA by the Environmental Protection Agency (EPA) [1] as a way to produce a relative-risk scale of potential groundwater vulnerability to pollution that could be applied to a large area was adopted and tested with GIS to identify areas from Dobrogea Region (Romania) where the groundwater is more or less susceptible to pollution.

1. Introduction
The general objective of this work is mapping of groundwater vulnerability to pollution, and preparation of vulnerability index maps using a parametric method and GIS. The specific objectives are: to produce dynamic GIS spatial data base and to provide map based information that assist decision/policy makers and land use planners for groundwater conservation and management, etc.

To achieve the above objectives, the empirical model known as “DRASTIC” with GIS was adopted. The empirical model known as “DRASTIC” is a parametric method used to identify areas where the groundwater is more or less susceptible to impact from pollution. The DRASTIC method was developed by the EPA and the National Water Well Association. According to the EPA DRASTIC guidance document [2], DRASTIC it can be used on a variety of scales, including sites (if they are large enough) to guide land development and resource protection. It can be modified to include or exclude parameters such as nitrates and pesticides and it can also serve as the basis for new methods for aquifer vulnerability assessment.

2. Materials and methods
In the Dobrogea - Littoral Basin Area, 10 groundwater bodies are identified and delimited. Of all these, 4 groundwater bodies belong to the permeable porous type (Holocene deposits, middle - upper Pleistocene stage), 4 groundwater bodies belong to the fisural-karstic type (developed in the Triassic and Sarmatian stage deposits) and 2 groundwater bodies belong to the karstic - fisural type (Jurassic stage) (figure 1).
2.1. Study area
From the quantitative and qualitative point of view all groundwater bodies in the study area are considered in good condition, with the mention that for all groundwater bodies they were recorded local exceedances of the quality standard or threshold values \[4\] for different indicators (e.g. NH\(_4\) - ammonium, Cl - chlorides, NO\(_3\) - nitrates, NO\(_2\) - nitrates and PO\(_4\) - phosphates). Sources of pollution that contribute to the deterioration of the quality of the groundwater are those that have the greater diffusion of pollution. In Dobrogea – Littoral Basin the following potential pollution sources have been identified:

- Human agglomerations due to lack of domestic or industrial wastewater collection systems;
- Agricultural activities (animal farms, excessive cultivation of agricultural land, farms, agricultural technics that do not have adequate manure storage systems and which use pesticides, etc.);
- Industrial activities (including landfills);
- Significant water catchments that may exceed the natural aquifer recharge rate.

The situation of the pollution sources for each groundwater body in the study area is presented in the following:

- The RODL01 - Tulcea groundwater body has the largest part of the area covered by cultivated land. If on the cultivated land are applied chemical fertilizers, than they may have a negative impact on the quality of the groundwater body;
- The RODL02 - Babadag groundwater body has almost equal coverage of forests and cultivated surfaces. The negative impact on the qualitative state of this groundwater body, determined by the application of chemical fertilizers on the cultivated surfaces, can determine changing the quality of this groundwater body;
- The RODL05 Central Dobrogea groundwater body has low impact pollution as a source of agricultural pollution on the qualitative state of the groundwater body. There is also a possible pollution from industrial sources (chemical industry, food industry). Much of the surface of the groundwater body is covered by agricultural land. Application of fertilizers on these surfaces could have a negative impact on the quality of the groundwater body;
- For the RODL08 Casimcea groundwater body as possible sources of pollution are diffuse pollution sources determined by agricultural units;
- The groundwater body RODL09 - North Dobrogea has on its surface agricultural land and forests. Thus, the quality state of the groundwater body is not significantly affected by a negative impact determined by the possible pollution from agricultural sources (the area is not proper to intensive agriculture). However, as possible sources of diffuse pollution we mention those from agriculture (mainly animal farms) and industry (food, extractive).

2.2. Data analysis
The concept of groundwater vulnerability to contamination is a useful tool for land use planning and
policy makers [5,6]. Many different methods have been developed for assessing groundwater vulnerability. The DRASTIC method is a qualitative method and was developed by the EPA as a way to produce a relative-risk scale of potential groundwater vulnerability to pollution that could be applied to a large area, while requiring relatively fewer data inputs compared to other vulnerability models and to understand which areas are more or less likely to be impacted by contamination from the surface migrating into aquifers. Due to the relative simplicity of DRASTIC compared to some other vulnerability assessment models, the large scale for which it is intended, and the qualitative nature of the results, DRASTIC should be thought of as a screening tool or as a “coarse-grained” look at aquifer vulnerability modeling that helps guide decisions and focus resources on areas that may require more detailed analyses, whether for land use decisions or environmental protection. Although DRASTIC is useful over large areas and serves as a good first step, ultimately, when making site-specific decisions on small, local areas, additional detailed site-specific hydrogeological modeling of contamination potential would be considered as an appropriate next step.

In order for DRASTIC to be properly utilized and the results of the DRASTIC analysis to be fully understood, it is necessary to understand the assumptions that the parametric method makes. The four key assumptions are: Contamination is introduced at the ground surface; Contamination is flushed into the groundwater by precipitation; Contamination has the mobility of water; Area being evaluated is 100 acres or larger. It would be an inappropriate use of the DRASTIC methodology to apply it in situations where these four assumptions are not valid.

To develop the relative-risk index, DRASTIC utilizes the hydrogeological factors that most significantly affect movement of contamination from the surface into an aquifer.

The seven hydrogeological factors, which form the acronym “DRASTIC” include:

- D – Depth to Water;
- R – Net Recharge;
- A – Aquifer Media;
- S – Soil Media;
- T – Topography (slope);
- I – Impact of Vadose Zone Media;
- C – Hydraulic Conductivity of Aquifer.

Once the analysis has been completed – ratings and weights assigned to each factor and the results summed – the resulting relative-risk index can then be symbolized on a map overlaying the study area, providing a qualitative analysis of the vulnerability to pollution.

DRASTIC index is computed by using the following equation:

\[ DI = DrDw + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw \]  

where: D, R, A, S, T, I and C = are the seven parameters stated before, \( r \) = rating of parameter, \( w \) = weight factor of parameter.

The importance of each factor in contaminant transport varies, therefore, each factor is assigned a relative weight on a scale of 1 to 5 (5 being the most significant). Further, each factor is divided into ranges or categories, to which is applied a rating. To develop the DRASTIC index for an area, the rating and weight of each factor are multiplied and the result for each factor is then added (table 1).

| Feature | Weight |
|---------|--------|
| Depth to water table | 5 |
| Net Recharge | 4 |
| Aquifer Media | 3 |
| Soil Media | 2 |
| Topography | 1 |
| Impact of Vadose Zone Media | 5 |
| Hydraulic Conductivity of Aquifer | 3 |

Replacing the corresponding weight values for each factor, equation (1) becomes:

\[ DI = 5Dr + 4Rr + 3Ar + 2Sr + Tr + 5Ir + 3Cr \]  

This equation allows obtaining vulnerability values (Drastic index) ranging from 23 to 230 as
shown in the following table 2 [5].

**Table 2.** The intrinsic vulnerability degree of aquifers according to DRASTIC.

| Aquifer vulnerability degree | Low | Moderate | High | Very high |
|------------------------------|-----|----------|------|-----------|
| DRASTIC index                | 0–100 | 101–140 | 141–200 | > 200 |

The rating factors take values from 1 to 10, they are used to reclassify the variation of the properties of each of the parameters used. For the preparation of this study the parameters used and their rating factors were taken from the DRASTIC guidance document (tables 3 - 9) [2]:

**Table 3.** Depth of water table.

| Depth (m) | Rating Dr |
|----------|-----------|
| 0 - 5    | 10        |
| 5 - 10   | 8         |
| 10 - 15  | 6         |
| 15 - 20  | 4         |
| >20      | 1         |

**Table 4.** Net recharge.

| Recharge (mm/year) | Rating Rr |
|--------------------|-----------|
| 0 - 50             | 1         |
| 50 - 100           | 3         |
| 100 - 175          | 6         |
| 175 - 250          | 8         |
| >250               | 9         |

**Table 5.** Geological formation of the aquifer.

| Aquifer lithology | Ranges | Rating Ar |
|-------------------|--------|-----------|
| Shale clay        | 1-3    | 2         |
| Metamorphic/magma rock | 2-5 | 3         |
| Metamorphic/erratic magma rocks | 3-5 | 4         |
| Glacial Till      | 4-6    | 5         |
| Sandstone         | 5-9    | 6         |
| Massive sandstone | 4-9   | 6         |
| Massive limestone | 4-9   | 6         |
| Sedimentary rocks (Sand or gravel) | 4-9 | 8         |
| Basalts           | 2-10   | 9         |
| Karstic limestone | 9-10  | 10        |

**Table 6.** Soil media.

| Type of soil            | Rating Sr |
|-------------------------|-----------|
| Thin or absent layer    | 10        |
| Gravel                  | 10        |
| Sand                    | 9         |
| Peat                    | 8         |
| Clay aggregate or compacted | 7         |
Sandy loam 6
Loam 5
Silty loam 4
Clay loam 3
Organic soil, root layer 2
Clay not compacted and not added 1

Table 7. Slope of the land.

| Slope (%) | Rating Tr |
|-----------|-----------|
| 0-2       | 10        |
| 2-6       | 9         |
| 6-12      | 5         |
| 12-18     | 3         |
| >18       | 1         |

Table 8. Geological material of the unsaturated zone.

| Nature of vadose zone | Ranges Ir | Rating Ir |
|-----------------------|-----------|-----------|
| Confining layer       | 1         | 1         |
| Clay/Loam             | 2-6       | 3         |
| Shale clay            | 2-5       | 3         |
| Limestone             | 2-7       | 6         |
| Sandstone, Bedded limestone, | 4-8 | 6         |
| Metamorphic / magma rock | 2-8 | 4         |
| Gravel and sand       | 6-9       | 8         |
| Basalt t              | 2-10      | 9         |
| Karstic limestone     | 8-10      | 10        |

Table 9. Hydraulic conductivity of the aquifer.

| Hydraulic conductivity (m/day) | Rating Cr |
|--------------------------------|-----------|
| Ranges                         |           |
| <1                             | 1         |
| 1-5                            | 2         |
| 5-20                           | 4         |
| 20-50                          | 6         |
| 50-100                         | 8         |
| >100                           | 10        |

This method is often used because the necessary data can easily be obtained. The final product is also easy to obtain, the finalized map being easy to interpret. The main disadvantage of the method is that the weighting system does not have a scientific basis. However, the DRASTIC method is most often used to assess aquifer vulnerabilities and the sensitivity analyzes performed over time have shown that the results of this method are very good. The large number of factors taken into account make this method one of the most complex, taking into account the possibilities of pollution from the land surface (through infiltration) as well as the possibilities of pollution transmitted through the phreatic layer. For each parameter, a raster map developed by GIS interpolation will be performed using the attribute data of the wells in the GIS database [7].

2.3. Building the model with ArcGIS

ArcGIS represents the system which joints two data bases. One data base operates with geometrical spatial objects and the second data base with the attributes of the information contained in the first one.
Data base flow chart to calculate DRASTIC index are presented in the following figure 2:

![Data base flow chart to calculate DRASTIC index](image)

**Figure 2.** Data base flow chart to calculate DRASTIC index.

To calculate the groundwater vulnerability index with ArcGIS, we have follow 3 steps in which we have used surface analysis (slope), interpolation, reclassification and map algebra, functions of the Spatial Analyst tool [8].

- **Step 1.** We have constructed the maps that represent the spatial distribution of each of the variables. For this proposes it was possible to use either deterministic (IDW, Spline) or geostatistical (Kriging) methods, but to illustrate the potential of ArcGIS we will work with IDW.
- **Step 2.** It consists of reclassifying the maps obtained for each of the variables according to the data reported in the tables from 3 to 9. This is done by means of the Reclassify - function of the Spatial Analyst extension. For the non-numerical data such as the geological formation that constitutes the aquifer, the soil cover under the surface of the land and the type of geological material of the unsaturated zone, an assessment is simply given to the type of material according to the previous tables to build the corresponding raster.
- **Step 3 - Algebra of maps.** With the maps already reclassified according to the previous step, what follows is to make the weighted sum of each of them. For this, ArcGIS has the Raster Calculator tool of the Spatial Analyst extension.

The result obtained in the previous step is reclassified according to table 2 to finally obtain the map of the DRASTIC intrinsic vulnerability index.

### 3. Results and discussion

In order to determine the vulnerability of aquifers in the study area, this region of the country was divided into 50 geomorphological subunits, and from hydrogeological point of view the hydrogeological characteristics of 80 wells were investigated.

For the calculation of the DRASTIC vulnerability index and in order to elaborate the final intrinsic vulnerability map, the DRASTIC method required the preparation of seven thematic maps, each one was classified and assigned ratings and weighted according to a range [9] (table 1).

The calculated DRASTIC index identifies areas, which are likely susceptible to groundwater contamination relative to each other. The higher DRASTIC index value, the greater is the relative groundwater contamination potential [10].

The DRASTIC vulnerability thematic map was obtained by running the model in the geographic information system (GIS) environment.

Using the Spatial Analyst tool- Raster Calculator function where each parameter was multiplied by a weighting factor according to its importance in the assessment we have elaborated the final DRASTIC Index map (figure 3).
Generally, the value of the vulnerability index determined by the DRASTIC method is between 0-230. For the study area the values obtained for the DRASTIC vulnerability index are between 60 and 170 (figure 4). Starting from the four classification degree of the DRASTIC index, in the present study case only the first three degrees are found (figure 5):

- Low vulnerability indices (0-100) – shades of yellow;
- Moderate vulnerability index (101-140) – shades of orange;
- High vulnerability index (141-200) – shades of red.

This high class is attributed to several factors, primarily the nature of the soil, namely porous-permeable to which the very low slope is added, which slows down the leakage process allowing the contaminant to penetrate into the aquifer both combined with a large amount of precipitation infiltrated into the soil. These contaminants originate in the present case from pesticides that are
administrated to predominantly agricultural land and from inappropriate disposal of farms waste. The coastal area is a particular case, where pollution is caused by the fact that this area is predominantly a tourist and industry area.

4. Conclusion

Parametric method DRASTIC can be a useful tool to model the vulnerability of groundwater. The results of applying the DRASTIC model should be used with care. This applies to a framework but does not take into account all the particularities of the released chemicals. GIS can help clarify the results of a complicated model through visual representation.

The DRASTIC method has the disadvantage of underestimating the vulnerability of groundwater bodies that are not porous-permeable;

In the studied area, the resulting vulnerability index is between 60 and 170. According to the vulnerability map of aquifers, most of Dobrogea's surface has moderate vulnerability (101-140).

High vulnerability areas (141-200) is found in the Oltina Plateau, Negru Voda Plateau, Macin Mountains, the Southern Black Sea Coast and the South-Eastern part of the Babadag groundwater body.

Vulnerability maps resulting from the use of this parametric method can be used by decision-makers to implement the groundwater protection strategy in the concept of sustainable development. These are particularly important in areas where the waters of these aquifers are used as a source of drinking water for the local population.

References

[1] Aller L, Bennet T, Leher J H, Petty R J and Hackett G 1987 DRASTIC: A standardized system for evaluating ground water pollution potential using hydrogeological settings Robert S. Kerr Environmental Research Laboratory, US Environmental Protection Agency Report 600/2-87-035 p 622

[2] US EPA (Environmental Protection Agency) 1985 DRASTIC: a standard system for evaluating groundwater potential using hydrogeological settings WA/EPA Series Ada Oklahoma p 163

[3] European Commission 2006 Directive 2006/118/EC on the protection of groundwater against pollution and deterioration

[4] Gogu R C 2000 Advances in groundwater protection strategy using vulnerability mapping and hydrogeological GIS databases (Belgium: Faculty of Applied Sciences, University of Liège) p 153

[5] COST 620 2003 Vulnerability and risk mapping for the protection of carbonate (Karst) aquifers, Final report (COST action 620) (Brussels, Luxembourg: European Comission, Directorat-General XII Science, Research and Development) p 297

[6] Evans B et al 1990 A GIS-based approach to evaluating regional groundwater pollution potential with DRASTIC J. Soil Water Conserv. 45 242-5

[7] Agua y SIG 2011 Determinación de la vulnerabilidad de un acuífero a través del método DRASTIC utilizando ArcGIS 9.3, Hidrología, Arcgis y Agua Subterránea Available: http://www.aguaysig.com/2011/02/determinacion-de-la-vulnerabilidad-de.html

[8] Napolitano P and Fabbri A G 1996 Single-parameter sensitivity analysis for aquifer vulnerability assessment using DRASTIC and SINTACS Application of Geographic Information Systems in Hydrology and Water Resources Management (Proceedings of the Vienna Conference) 235 559-66

[9] Javadi S, Kavehkar N, Mousavizadeh M H and Mohammadi 2011 Modification of DRASTIC model of map ground water vulnerability to pollution using nitrate measurements in agricultural areas J. Agr. Sci. Tech. 13 239-49